TECHNISCHE UNIVERSITÄT MÜNCHEN

Lehrstuhl für Baurealisierung und Baurobotik

Methodological development for exploring the potential to implement on-site robotics and automation in the context of public housing construction in Hong Kong

Wen Pan

Vollständiger Abdruck der von der Fakultät für Architektur der Technischen Universität München zur Erlangung des akademischen Grades eines

Doktor-Ingenieurs (Dr.-Ing.)

genehmigten Dissertation.

Vorsitzender: Prof. Florian Musso

Prüfer der Dissertation: 1. Prof. Dr.-Ing. Thomas Bock

2. Prof. Dr.-Ing. habil. Alexey Bulgakov

3. Prof. Hou Hetao

Die Dissertation wurde am 07.04.2020 bei der Technischen Universität München eingereicht und durch die Fakultät für Architektur am 01.07.2020 angenommen.

Acknowledgement

Having the opportunity to carry out this research and undertaking this Ph.D. has been a life-changing experience for me and this achievement would not have been possible without the kind support and guidance from many people. I wish to express my deepest gratitude to all who assisted me in the preparation of the concept development and writing of the thesis. Above all, I would like to thank my Ph.D. advisor, Prof. Dr.-Ing. Thomas. Bock, for granting me the opportunity to pursue a Ph.D. as well as his many years of contributions of time, advice, knowledge, and motivation. He both introduced me to the topic of construction robotics and guided my research aspirations on this fascinating topic. It has been an honour to be his Ph.D. student and candidate. The experience that I have gained over the years with the Chair of Building Realization and Robotics will be highly valuable for my future. In addition, I would like to thank Prof. Hetao Hou for supporting this work.

I would also like to thank Dr. T. Linner for his support and instructions over the years and his great efforts on managing the Construction Industry Council Hong Kong (CIC) consultancy project. I would next like to thank Dr. K. Langosch, Dr. J. Güttler, and Mr. A. Bittner for their tremendous support and guidance over my Ph.D. study, especially in the areas of project planning, technical support, and academic writing. In addition, I would like to thank Ms. R. Schlenker for her kind support and other demanding administrative tasks.

I would like to offer my sincerest thanks to the Construction Industry Council Hong Kong (CIC) for initiating and funding this research. Numerous other companies and organizations have contributed and offered assistance during the project: Hip Hing Construction Co., Ltd offered exclusive support for the on-site visit, HERO GmbH assisted with mock-up building, and the Hong Kong Housing Authority provided assistance during the initial research phase. In addition, I would like to thank the following companies for their support during the dissertation-writing period, nLink AS, TyBot, Construction Robotics, FBR Ltd, OKIBO, Les Companions, and Robot At Work.

I also would like to express my gratitude to Dr. Bahriye Ilhan, S. K. Ernstsen, Dr. R. Li, and Dr. C. O’Meara, as both researchers and friends, for their support, advice, and collaboration. Many thanks to F. Tollefson, and B. D. Koehnlein for writing advice and proofreading.

In addition, I would like to offer my sincere thanks to my colleagues H. Rongbo, K. Iturralde, C. Zhao, and M. Schlandt for their friendship, motivation and support. Furthermore, I am thankful to Prof. Dr.-Ing. hab. Alexej Bulgakow, Prof. Hou Hetao, and Y. Watanabe for sharing their knowledge and expertise whilst researching with the Chair. I would like to thank them for the inspiration and ideas developed during the research phase.

Finally, I would like to thank my parents and family for all of their support throughout my educational life and beyond. Particularly, I would like to thank my wife Dilara for her continuing motivation and unconditional support, understanding, and encouragement throughout my Ph.D. study. Without their support, nothing I have accomplished would have been possible.

Zusammenfassung

Die Bauindustrie wird oft als konventionell erachtet, bleibt sie doch in ihrer allgemeinen Leistungs-fähigkeit sowie bei der Geschwindigkeit der Übernahme innovativer Technologien weit hinter ver-gleichbaren Industriezweigen, beispielsweise der Fertigungsindustrie, zurück, wo die Einführung von Automatisierung und Robotik Produktivität, Sicherheitsniveau und Qualität gesteigert hat. Können Automatisierung und Robotik das Bauwesen auf eine vergleichbare Art und Weise beein-flussen? Wenn diesen Technologien ein solches Potential innewohnt, dann ist es notwendig, die Frage zu stellen, wie man die betreffenden innovativen Technologien in eine stagnierende Bauin-dustrie einführen kann.

Zwar unterscheidet sich die Bauindustrie grundsätzlich von der Fertigungsindustrie und es gibt eine ganze Reihe von Herausforderungen für das Einführen von Automatisierung und Robotik, doch sind diese Unterschiede und Herausforderungen nicht unüberwindbar. In der Bauindustrie gibt es Sta-keholder auf mehreren Ebenen, davon jeder mit seinem Partikularinteresse, seiner Expertise und seinem Verantwortungsbereich. Baupraktiker, Behörden und potentielle Investoren sind mit der Technologie nicht vertraut, was wiederum ihre Bereitschaft reduziert, Veränderungen zu akzeptie-ren, die möglicherweise weitere Umbrüche für bestehende Wertschöpfungsketten und Infrastruk-tur zur Folge haben.

Hinzu kommt, dass es einen Mangel an interdisziplinärer Zusammenarbeit in der Bauindustrie gibt, der die Einführung der hier vorgestellten Technologien weiter erschwert. Der Trend, Automatisie-rung und Robotik zur Lösung von baubezogenen Aufgaben einzusetzen hat seinen Ursprung in den 1980er Jahren in Japan. Über Jahre hinweg wurden eine Vielzahl von Baurobotiksystemen entwi-ckelt, doch nur wenige erfolgreich vermarktet.

Herauszufinden, wie die Entwicklung eines Bauroboters von der Konzeptphase bis zur Marktfähig-keit umgesetzt werden kann, ist der bestmögliche Weg, um die notwendigen Leistungsparameter sicherzustellen und die Marktfähigkeit der Technologie zu verifizieren. Allerdings wurde eine sys-tematische und wissenschaftliche Herangehensweise an diese Aufgabe, insbesondere mit engem Bezug zur Industrie und den Behörden, bisher noch nicht eingehend untersucht. Vor diesem Hin-tergrund wird in dieser Dissertation mithilfe einer ausführlichen Fallstudie ein umfassender metho-discher Entwicklungsprozess für die Herangehensweise an die Einführung von Automatisierung und Robotik in der Bauindustrie, dargelegt.

Die Fallstudie basiert auf der ersten Phase eines vom Construction Industry Council Hong Kong (CIC) geförderten Beratungsprojekts. Das CIC-Projekt bot eine einzigartige Möglichkeit für einen fach-übergreifenden Dialog zwischen der Bauindustrie und der Wissenschafts- und Forschungsgemein-schaft, hinsichtlich der Ermittlung des Potentials einer Einführung von Automatisierungs- und Robo-tertechnologie in den Bereich des öffentlichen Wohnungsbaus.

Die erste Phase des CIC Projekts wurde in mehrere Stufen unterteilt, darunter vorbereitende For-schungsarbeiten, eine Umfrage, ein co-creation workshop, ein erster Entwurf, ein Versuchsmodell und eine Vorführung. Das Befolgen des obengenannten Stufenprozesses ermöglichte die Entwick-lung einer systematischen und fundierten Entscheidungshilfe um die Herausforderungen des öf-fentlichen Wohnungsbausektors in Hong Kong zu erfassen, die

Stakeholder und ihre Anforderun-gen zu verifizieren, die Aufgabe mit dem höchsten Automatisierungspotential zu identifizieren, den optimalen Entwurf zu bestimmen und schließlich die passende Geschäftsstrategie für eine zukünf-tige Vermarktung des Produkts zu entwerfen.

Das Projekt in seiner Gänze kann als umfassender Leitfaden für die Entwicklung eines Entschei-dungshilfeprozesses zusammengefasst werden, der der Baubranche und darüber hinaus helfen kann, innovative und kompatible Lösungen für die Einführung von Robotertechnologie anzustoßen und zu erforschen.

Abstract

The construction industry is often considered conventional with the overall performance as well as the speed of adopting innovative technologies lagging behind other similar industries, especially the manufacturing industry where the implementation of automation and robotic technologies has improved manufacturing productivity, safety, and quality. Can automation and robotics technology similarly influence the construction industry? If it has the potential, then it is essential to ask how to introduce the proposed innovative technology into the stagnant construction industry. The construction industry is fundamentally different from the manufacturing industry and there are various challenges when attempting to implement automation and robotics technologies, but these differences and challenges are not insurmountable. The construction industry consists of multiple levels of stakeholders and each carries a unique set of interests, expertise, and responsibilities. The construction practitioners, regulators, and potential investors are not familiar with the proposed technology, which decreases the willingness to accept changes that may impose additional changes on the existing supply chain, as well as the infrastructures. In addition, there is a lack of cross-disciplinary collaboration within the construction industry, which makes implementing the proposed technologies even more challenging. The trend of using automation and robotics to solve construction-related tasks was initiated in Japan in the 1980s. Over the years, many construction robotics systems have been developed, yet very few have been commercialized. Consequently, exploring how to transform a construction robot from the conceptual stage to the market uptake stage is the optimal way to ensure the appropriate performance parameters and to verify the marketability of the proposed technology. However, the systematic and scientific method to approach this type of task, primarily when closely associated with the industry and authorities, has not been comprehensively discussed. Thus, the dissertation will develop a comprehensive methodological development process for exploring how to implement automation and robotic technology in the construction industry with the support of an extensive case study that is closely linked with the construction industry.

The case study is based on the first phase of the consultancy project funded by the Construction Industry Council Hong Kong (CIC). The CIC project provided a unique opportunity for communication and cross-consultation between the construction industry and the academic research community, which explored the potential to implement automation and robotics technologies in the public housing construction (PHC) sector. The first phase of the CIC project has been divided into several stages, including initial research, a survey, a co-creation workshop, the initial design, a mock-up, and demonstration activity. By following the stages above, systematic decision-making tools were developed to identify the challenges faced by Hong Kong PHC sector, to verify stakeholders as well as their requirements, to define which task has the most potential to be automated, to determine the optimal design specifications for the proposed system, and to ultimately introduce the appropriate business strategy that facilities the future commercialization of the product. The entire project can be summarized as a comprehensive guideline that can be used as a development decision tool that assists the construction industry and beyond as to when to initiate and explore innovative and compatible solutions to the implementation of robotic technologies in the future.

Table of Contents

List of Figures

List of Tables

Glossary

A

Admission Scheme for Mainland Talents and Professionals (ASMTP): ASMTP is an immigration scheme that attracts mainland talents and professionals to seek employment opportunities in Hong Kong to address local skill shortage issues as well as boost the local economy.

Artificial intelligence (AI): In this work, AI addresses the integration of sensors and actuators that increases reasoning about physical objects that enables robots to be aware of the working environment and to improve their performance through machine learning technology.

Alternating Current (AC): AC is an electric current that normally flows in a back-and-forth sequence, in contrast to Direct Current (DC).

Automated Guided Vehicle (AGV): The **AGV** is also called a self-guided vehicle and it is commonly used for logistic purposes in warehouses, distribution centres, and production facilities. There are many types of AGVs available based on various applications and payloads, such as forklift AGV, towing AGV, and heavy-duty AGV.

Architectural Institute of Japan (AIJ): The **AIJ** is a Japanese institution for architects and construction practitioners.

Architectural Services Department (ASD): The **ASD** is one of the Hong Kong government departments that are in charge of developing and maintaining public facilities in the territory.

ArchiCAD: ArchiCAD is an architectural BIM CAD design software developed by Graphisoft.

Apache Hadoop (AH): The **AH** is a decentralized open-source software that deals with large data by breaking down and distributing large data into smaller clusters by using simple programming models.

Apache Spark (AS): The **AS** is an open-source unfiled analytics software engine for large data processing and machine learning.

Agile product development (APD): The concept of **APD** is used in incremental product development processes and encourages customer involvement from an early stage as well as providing feedback.

B

Building information modelling (BIM): BIM is an architectural application supported by various tools, technologies, and software. BIM integrates construction-related data and provides digital insight into the actual construction project.

Building Department (BD): BD is a government department in Hong Kong that is responsible for building planning, regulations, safety, and inspection.

Building Service Inspector (BSI): The **BSI** is a professional occupation in the Hong Kong construction sector. The primary duties of a BSI are administration, inspection, monitoring, and scheduling various aspects of construction tasks.

Bin picking: The terminology of bin picking in this work is referring to a robot to pick and place the object by using sensors and vision systems.

Building Contractors Society (BCS): The **BCS** was launched in 1959 in Japan with an aim to embrace architectural excellence through the design, construction method, and technology.

Building Environmental Assessment Method (BEAM): The **BEAM** is a green building labelling and standardization tool that was implemented in Hong Kong. The BEAM aims to improve the environmental performance of a building's lifecycle, enhance the living quality and standards of its occupants, and proactively contribute to sustainable development in Hong Kong.

Biofine Sealer: It is a water-based styrene acrylic sealer. It is commonly used on buildings' façade to prevent fungus growth and alkalinity.

Banks man: A **Banks man** is a professional construction occupation with the duty of directing cranes or vehicles while loading and unloading goods.

Big data (BD): BD refers to the field that deals with the method to create, gather, process, and transfer a large quantity of complex data at a rapid speed.

Big Data Engineering (BDE): **BDE** are those activities conducted by BD engineers dealing with BD processing, development, maintenance, and monitoring.

Big Data Analytics (BDA): BDA is a process to investigate complex BD with specific aims. The BDA method has been integrated into many industries to improve their decision-making processes.

C

Construction automation: In this work, **construction automation** refers to construction tasks that are augmented or replaced by integrating automation technologies.

Construction robotics: Construction robotics is addressing robotics technologies that have been developed to solve specific construction-related tasks.

Cost-benefit analysis (CBA): A **CBA** is a process to identify the relationship between tangible costs and profits of a product or project. The method is often used as a decision-making tool to determine whether the project or product is worth investing in.

Construction Innovation and Technology Application Centre (CITAC): CITAC serves as an innovation hub that showcases state-of-the-art technologies from Hong Kong and abroad.

Cost-effectiveness analysis (CEA): CEA is distinct from CBA; it is used to analyse relative cost, non-monetary value, and incremental costs of various periods, causes, and milestones.

Compound annual growth rate (CAGR): CAGR is used to measure the growth rate from the initial investment value to the end of the investment value.

Construction Industry Group (CIMCIG): CIMCIG is a UK organization that improves marketing efforts of the construction industry and promotes best practice.

Census and Statistics Department (C&SD): The **C&SD** is a government department that supplies social and economic official statistics in Hong Kong.

Civil Engineering and Development Department (CEDD): The **CEDD** is a government department whose main duties are planning and overseeing infrastructure construction.

Construction Workers' Registration System (CWRS): The **CWRS** is a registration system for construction workers. The Construction Workers Registration Ordinance (CWRO) enforces CWRS to be implemented.

Contractor Cooperative Training Scheme (CCTS): The **CCTS** is a training scheme that allows the worker to receive subsidized training provided by the employer.

Construction Innovation and Technology Fund (CITF): The **CITF** is a Hong Kong government initiative that embraces innovation in the construction sector.

Certificate of Compensation Assessment: The **Certificate of Compensation Assessment** is issued by the Commissioner for Labour and deals with compensation matters regarding employees who suffer work-related injuries or occupational diseases.

Clerk of Works, (COW): The **COW** is a professional construction occupation that is usually employed by the client. The duties of a COW are inspecting building quality and on-site operational safety.

Collaborative Workspace (CWS): CWS are offices where employees of various companies (of various sizes) work in a common space.

Construction Industry Safety Card: A **Construction Industry Safety Card** is required by the Hong Kong construction industry when operating on any construction or engineering site. The applicant will receive a mandatory basic safety-training course.

Collaborative Project Scheme (CPS): The **CPS** is a funding scheme administered by the Construction Industry Council (CIC), which includes the funding scheme for the co-applicant and the industry partner.

Chief Executive Officer (CEO): A **CEO** is someone who in charge of a company and has the power to make the majority of business-related decisions as well as managing and overseeing the operation of the company.

Chief Technology Officer (CTO): A **CTO** is someone who is in charge of research and development and fulfils the technological requirement of a company.

Certification of Electrotechnical Equipment and Components (CB Scheme): The **CB Scheme** is an internationally recognized system for safety certification for electrical and electronic equipment, devices, and components.

CE marking: CE marking is a certification mark that confirms the product complies with the relevant health and safety as well as environmental protection requirements in the European Union.

CPCS operator card: CPCS stands for Construction Plant Competence Scheme, which is a training scheme for construction plant operators in the UK. Any applicant who completes both theory and practical tests will receive the **CPCS operator card** and become a qualified operator.

D

Degree of Freedom (DOF): In the context of robotics, **DOF** is used to define the numbers of independent displacements and motion capabilities of the robot joints.

Degree of Automation (DOA): In this work, **DOA** is addressing the rates of automation applied in a robot. DOA is used to define the optimal level of automation to be adopted in a construction task as opposed to the manual tasks.

Development Bureau: The **Development Bureau** is a Hong Kong government department in charge of urban planning and renewal projects.

Design for manufacturing and assembly (DfMA): DfMA is an engineering strategy commonly used in modern manufacturing sectors. The principle of DfMA is to simplify the design of the product and, ultimately, to improve assembly efficiency.

Dawan (Great bay area): The **Dawan** area consists of nine cities in Guangdong province and Macau and Hong Kong.

Direct current (DC): DC is an electric current that always follows the same direction, in contrast to Alternating Current (AC).

Dynamic Stabilisation Technology (DST™): The Australian construction robotic company FBR developed the **DST™**. The technology assists robots in measuring and adjusting movement caused by wind, vibration, and inertia.

Denavit-Hartenberg parameters (D-H): D-H is a conventional methodology commonly applied in mechanical engineering and robotics. In this work, D-H is used to determine the kinematics and dynamics of the proposed robot.

Demand readiness Level (DRL): The **DRL** provides a method to measure and determine the maturity of the market demand of the innovation.

E

Enhanced Construction Manpower Training Scheme (ECMTS): The **ECMTS** provides funding and incentives for the Hong Kong construction industry to train semi-skilled workers.

The aim of ECMTS is to tackle the skilled labour shortage and to attract a new workforce to join the construction industry.

End effector: In the context of robotics, an **end effector** is referring to the device equipped in the last joint of the robotic arm. An end effector often sustains a specific function according to the application of the robot.

Environmental Protection Department (EPD): The **EPD** is a Hong Kong government department in charge of environmental protection and sustainable development of Hong Kong.

Employees Retraining Board (ERB): The **ERB** is a Hong Kong statutory body that offers market-oriented training and funds to satisfies changing employment demands in the labour market.

Electrical and Mechanical Services Department (EMSD): The **EMSD** is a Hong Kong government department that performs regulatory enforcement activities regarding the electrical and mechanical installation and gas and lifts safety-related areas.

F

Factory Acceptance Test (FAT): The **FAT** is a testing process to determine if the finished product is built and operates according to the specifications.

Foundation Classes file (IFC): The **IFC** is a neutral data standard that is commonly used for openBIM data exchange. In this work, the IFC is used for data management purposes.

IFC File Analyzer (IFA): The **IFA** is a software platform that translates IFC files into the desired formats required by the engineers.

G

Gross Domestic Product (GDP): GDP indicates the total value of products and services generated in a region under a specific period.

Graphical user interface (GUI): A **GUI** is a form of interface that allows users to engage, control, and use devices through graphical features such as icons, digital buttons, and symbols.

Gondola: In this work, a **gondola** refers to a suspended working platform.

Gazebo: Gazebo is an open-source simulator that provides a 3D simulation environment to test robotic designs.

German Space Operation Center (GSOC): The **GSOC** is part of the German Aerospace Center (DLR) and performs mission control operation and astronaut training programs.

H

Hong Kong Dollar (HK$): The **HK$** is the official currency of Hong Kong; at the time of writing, 1 HK$ is the equivalent of 0.21 Euro (HK$1.00 = 0.21€ OR 1.00€ = HK$8.59)

Hong Kong Construction Association (HKCA): The **HKCA** is a Hong Kong government department with the aim to improve the construction standard in Hong Kong. Over 300 local construction companies have joined the association.

Hong Kong Confederation of Trade Unions (HKCTU): The **HKCTU** is an independent union in Hong Kong with the interests of improving works rights and welfare.

Hong Kong Institute of Construction (HKIC): The **HKIC** is a member of the Construction Industry Council (CIC) and is aiming to provide a high standard for the workforce of the Hong Kong construction industry.

Hong Kong Housing Authority (HKHA): The **HKHA** is a government agency that provides public housing in Hong Kong.

Hong Kong Housing Society (HKHS): The **HKHS** is an independent, non-government organization that provides public housing for Hong Kong residents.

Homeownership Scheme (HOS): The **HOS** is a subsidized- sale scheme developed for the public housing market and managed by HKHA.

Hong Kong Science and Technology Parks Corporation (HKSTP): The **HKSTP** is a statutory body that aims to promote Hong Kong as the regional hub for technology and innovation.

Hetao District: Hetao District is located in North-western China. The region is less developed when compared with the eastern part of China.

Human-robot interaction (HRI): In the context of robotics, **HRI** is a scientific field that deals with human feelings towards robots and the interaction methods between humans and robots.

Hong Kong Federation of Trade Unions (HKFTU): The **HKFTU** is the largest labour group in Hong Kong and is closely associated with the HKCTU.

Hong Kong Automation Technology Council (HKATC): The **HKATC** consists of industry partners in Hong Kong from many disciplines who embrace cross-industry collaboration and specialize in advanced production methods, automation and robotics, and electronic systems.

Hong Kong Service Suppliers (HKSS): The **HKSS** is an individual party; the party representative is obliged to apply the HKSS certificate prior to trading and providing service in Mainland China.

Human-computer interaction (HCI): HCI is a research area that focuses on how humans interact with a computer and evaluate the best practices when concerning interface development.

Hong Kong Building Department (HKBD): The HKBD is a government department that issues building regulations, guidelines, and inspections of new-build projects as well as building alteration works.

I

Information and Communications Technology (ICT): ICT refers to technologies used for telecommunication, digital information technology, media, and other digital data management systems.

Innovation and Technology Fund (ITF): ITF is a Hong Kong government-funding scheme, which covers multiple funding programmes to support innovation initiatives of local businesses.

International Federation of Robotics (IFR): The **IFR** is a non-profit organization that consists of global robotics companies and professionals. IFR aims to promote technological development and identify market trends.

Internet of Things (IoT): The concept of **IoT** refers to the Internet being ubiquitous and the IoT network being able to connect all things and people through data collection, transfer, and processing without physical or computer interactions.

Internet of Building Things (IoBT): The **IoBT** concept deals with building data by using IoT technologies. The concept can be achieved by adopting Building Information Modeling (BIM) in conjunction with sensors and real-life data.

Industry 4.0: Industry 4.0 commonly refers to the digital transformation of the manufacturing sector. In this work, industry 4.0 is referring to digitalization, automation, and IoBT in the construction industry.

Intellectual property (IP): IP is a type of intangible human creation of intellectual goods that might have commercial value later. In this work, IP addresses construction robotics-related patents.

Innovation and Technology Bureau (ITB): The **ITB** is a Hong Kong government department, and is in charge of innovation and technology-related policy-making as well as offering incentive schemes to encourage innovation initiatives.

Innovation and Technology Commission (ITC): The **ITC** is a government policy bureau responsible for policy matters in regards to innovation and technology development and offering financial support for innovative local businesses.

Intelligent assist devices (IADs): In general, **IADs** are devices based on mechatronics, automation, or pneumatic technology to provide assistive motions or features. IAD technology is implemented in the manufacturing sector, especially when dealing with human-machine collaboration.

Integration readiness level (IRL-1): The **IRL-1** provides a method to measure and determine the maturity of compatibility and the possibility of integration between one system and another.

Innovation readiness level (IRL): The **IRL** evaluates the product development milestones and offers guidance about the product development process.

J

Just-in-Time (JIT): JIT is a supply workflow management theory developed by Toyota. JIT emphasizes small lot size, pull instead of push, reduction of defects, and maximizing material flow efficiency in manufacturing.

Just-in-Sequence (JIS): JIS goes hand-in-hand with JIT. It is an inventory management theory that says the components or parts should arrive at the right job station when needed.

Java: Java is a programing language that can be used to script computer programs, mobile devices, servers, and other smart devices.

K

Key Performance Indicator (KPI): KPI is a performance measurement tool that identifies tangible or intangible properties that can be used to evaluate the specific performance of a product, project, or organization. In this work, KPI is used to evaluate construction robotics performances.

Kinematics: In this work, **kinematics** is used to describe robotic motion and geometry. It helps to understand the DoF and control principles of the proposed robot.

L

Long Term Housing Strategy (LTHS): The **LTHS** is a Hong Kong government strategy tackling the shortage of public housing by providing financial support and ownership schemes for first-time buyers.

LiDAR: LiDAR stands for Light Detection and Ranging, which uses sensors and lasers to sense and measure the target object. The method is used in many industrial surveying practices.

Logistics and Supply Chain MultiTech R&D Centre (LSCM): The **LSCM** was funded through ITF and deals with the development and implementation of logistic and supply chain technologies in Hong Kong and Mainland China.

List approach: Paul Morris Fitts proposed the **List approach** in 1954. It focuses on function allocation research and in this work, it was carefully investigated to evaluate human and robot function allocation.

Labour Department (LD): The **LD** is a Hong Kong government department that is responsible for employment rights, health and safety, and reinforcing excellent employment practices.

M

Modular Integrated Construction (MiC): MiC is a type of 3D volumetric building system that utilizes prefabricated off-site services, appliances, and fully integrated finishing.

Musculoskeletal disorders (MSDs): MSDs is a medical condition that affects muscles, bones, and joints. Heavy physical work can increase the chance of MSDs occurring.

Metabolism: In this work, **metabolism** refers to the post-war architectural moment that embraced the concept of buildings or cities being similar to a living organism in that they are constantly changing and growing.

Machine learning (ML): ML is a scientific topic closely related to AI, but is the notion of empowering robot applications to learn from previous experiences without using instructive input.

Methods-Time Measurement (MTM): MTM is a method to estimate time spent on a manual operation for producing a product, based on estimation.

Matlab: Matlab is a computing environment commonly used by robotic engineers and in this work, the controller of the stabilization system was developed by using Matlab.

Manufacturing readiness level (MRL): The **MRL** provides a method to measure the maturity of the manufacturing ability of the given product, components, and parts.

N

Non-Governmental Organizations (NGOs): NGOs are usually independent organizations with non-profit missions.

Non-Destructive Testing (NDT): NDT is an industry testing and analysis method to evaluate the properties and defects of materials, products, and systems.

Net Present Value (NPV): NPV represents the difference between the current cash flow value and the future cash flow value within a specified period under predetermined discount rates.

O

"Open Door" policy: In 1978, an **"Open Door" policy** was adopted in China when China transformed from a self-sufficient economy to an open-market economy that was accessible to other nations, especially the western developed nations.

On-site construction robotics (OCR) (the proposed OCR): The **OCR** refers to a construction robotics application that was developed predominantly for on-site construction tasks. In this work, **the proposed OCR** refers to the proposed multifunctional façade finishing robot.

Open-building (OB): The **OB** concept is an architectural approach that separates buildings into different levels, such as support and infill. The concept allows the building to be more flexible and adaptable.

P

Public Housing Construction (PHC): In this work, **PHC** is a Hong Kong public residential housing construction.

Pearl River Delta Metropolitan Region (PRD): The **PRD** is in the Guangdong province, the region that possesses the largest manufacturing economy in China.

Public rental housing (PRH): PRH is a type of public housing provided by the Hong Kong Housing Authority and provides affordable rental accommodation for low-income households, single elderly persons, and the unemployed.

Pay for Safety Scheme (PFSS): The **PFSS** is an incentive scheme to encourage contractors to increase their efforts to improve health and safety measures in daily operations.

Performance Assessment Scoring System (PASS): PASS assessments consist of work assessment and general assessment. The PASS system aims to maintain the standard and quality of new building works.

Programmable Logic Controller (PLC): A **PLC** is a computerized controller for industrial equipment and is equipped with an on-board operating system. PLC influences the operation process of the allocated device.

Python: Python is a high-level, open-source programming language that is commonly used by software developer and researchers.

Power-interest Grid: A **Power-interest Grid** is a method for categorizing stakeholders based on their interests and hierarchy structure.

Product conformity certification schemes (PCCS): The **PCCS** is a certification scheme that covers all aspects of building materials, products, and systems. Only certified products can be used in the construction project.

Protimeter: The **Protimeter** is a handheld survey device to detect the level of moisture and dampness in building surfaces.

Precast concrete façade (PCF): In this work, **PCF** refers to the off-site prefabricated concrete wall that is non-load bearing.

Proportional–integral–derivative controller (PID): The **PID** controller is a control loop feedback system that is widely used in many industrial and automation applications.

Proof of concept (PoC): The **PoC** is a process to validate an early design about a product that has the potential to be realized in the real world.

Product development processes (PDPs): PDPs demonstrates the overall process that a new product is being developed. It often reflects the steps involved from the initial concept to the final product.

Phase-gate (PG): The **PG** is a project management method that divides the project into smaller, more manageable phases. Each PG also represents a clear roadmap that assists the project management team in making critical decisions.

Physical human-robot interaction (pHRI): pHRI is a scientific research topic dealing with topics of active safety and close-range human-robot collaboration.

Policy readiness level (PRL): The **PRL** provides a method to evaluate the level of willingness that a government or other organization exhibits to change an existing policy or in issuing a new policy corresponding to a new product requirement.

R

Research and Development (R&D): R&D refers to the efforts companies spend on developing new technologies, products, or services. R&D is an incremental process in terms of product iteration and maintaining a competitive edge.

Railway Development Strategy (RDS): RDS is a railway network expansion strategy that offers a framework for railway project planning.

Radio-Frequency Identification (RFID): RFID uses radio waves to detect, capture, and process data stored in a tag or label. RFID can be attached to objects, buildings, and mobile devices.

Robotics and Autonomous Systems (RAS): RAS is a U.S. Army research initiative that combines AI technology and robotics and aims to develop advanced autonomous defence systems.

Robotics Catalysing Centre (RCC): The **RCC** facilitates robotics-related projects in Hong Kong. The centre offers working spaces and workshop facilities for prototyping and product development.

Ruby: Ruby is a high-level open-source programming language.

Robot Operating System (ROS): ROS is an open-source framework that provides features and functions of an operating system but is not an operating system.

Robot-Oriented-Design (ROD): Professor Thomas Bock proposed the concept of **ROD** in 1988, highlighting that construction infrastructures or buildings should facilitate the use of robotic technologies. More simply put, it is the idea that the construction environment should become robot-friendly.

Revit Architecture: The **Revit Architecture** is a Building Information Modeling (BIM) software for architects, engineers, and academics.

R language: R language is a programming language developed for statistical and graphical analysis.

Residual Current operated Circuit-Breaker (RCCB): The **RCCB** is an electrical device that prevents electric shock as well as system damage by cutting off an electronic circuit.

S

Special Administrative Region (HKSAR): HKSAR stands for the Hong Kong Special Administrative Region. The HKSAR operates under the “one county, two systems” concept.

Supplementary Labour Scheme (SLS): The **SLS** is a Hong Kong government scheme that allows employers to import skilled labour from outside Hong Kong with the aim of addressing the labour shortage issue.

Slip form system: In comparison with the conventional formwork system, the **slip form system** allows constant concrete pulling allowing the formwork to continue to rise vertically by using hydraulic jacks. The slip form system is more economical and faster than the conventional method.

Super Construction Factory (SCF): The **SCF** is a self-climbing facility situated on the top of a build that is under construction. The SCF consists of an overhead crane system, vertical material delivery system, material loading bays, and control room.

Scala: **Scala** is a high-level programming language that offers comprehensive libraries for developers.

System readiness level (SRL): The **SRL** is a methodology developed to evaluate overall system maturity.

T

Transport and Housing Bureau (LTHS): The **LTHS** is a Hong Kong government department that supports all public housing-related matters. The LTHS is working closely with the Housing Authority (HA).

TIMWOOD: The **TIMWOOD** defines the seven wastes in manufacturing: transportation, inventory, movement, waiting, overproduction, over-processing, and defects. The terminology is used in lean manufacturing topics.

Technology readiness levels (TRL): The **TRL** provides a measurement system to evaluate the maturity levels of a certain technology.

Town Planning Board, Government Property Agency (GPA): The **GPA** is a statutory body of the Hong Kong government and is responsible for urban planning and development to improve the living standards of the local community.

Tekla Structures: **Tekla Structures** is a BIM software that offers exclusive coverage of building parts, components, and materials.

U

Urban Renewal Authority (URA): The **URA** is a Hong Kong statutory body in charge of urban renovation, maintenance projects, and improving the existing building conditions across Hong Kong.

V

Visual Basic: Visual Basic is an event-based programming language, and it is relatively easier to learn for beginner programmers.

Vocational Training Council (VTC): The **VTC** is the largest vocational and professional training provider in Hong Kong.

Virtual reality (VR): VR is a computer technology that offers simulated visual experiences for its users.

1 Introduction

1.1 General background

When compared to the other industries, the construction industry is often considered highly conventional. It has been slowing down in productivity, it is generally lacking in skilled labour, it is often highly risky, and it has been steadily increasing in cost. Hence, "Dirty, Dangerous and Demeaning," also known as the 3Ds, are often associated with the construction sector as is evident from the situation around the world (Holumyong *et al.*, 2018). On the other hand, some industries, particularly the manufacturing industry, have adopted robotics and automation technologies in recent years and this has resulted in increased productivity, affordability, quality, and safety. In order to transform the unfavourable image of the construction industry, there is an increasing trend in adopting automation and robot technologies into the construction industry among many engineers, architects, and authorities. Notably, the construction industry is different from the manufacturing industry, specifically in the way that products are planned, designed, produced, delivered, consumed, maintained, and recycled. The nature of a building, the construction method, the intended usage of a building, and a building's lifecycle are much more complicated than a typical consumer product. Because of this, identifying the ideal degree of automation, kinematic, mechatronic complexity, end-effector design, sensor technology, control method and computational complexity for construction robots is a highly complex and sophisticated undertaking. Therefore, successfully selecting, proposing, designing, and implementing appropriate automation and robotic technology for the construction sector is a challenging task. A systematic approach is necessary, not only in the technological aspects, but also when investigating stakeholder requirements and when addressing economic, managerial, technical, social, and political aspects.

To narrow the research scope, this study will use public housing construction (PHC) in Hong Kong as a case study to explore which automation technologies can be applied in public housing development in Hong Kong and will develop practical strategies and action plans for implementing those identified technologies in Hong Kong on the construction site. The detailed description of the research scope will be illustrated in a later section. Hong Kong is perfect for a case study due to its unique circumstances in terms of its geographic location, demographics, and economic factors. The Hong Kong PHC is experiencing challenges of an ageing workforce and stagnant productivity and is therefore urgently searching for feasible solutions to change and transform its performance. In view of this, the Construction Industry Council Hong Kong (CIC) Committee on Productivity commissioned the Chair of Building Realization and Robotics (br^2) at Technical University of Munich (TUM) to consult on the Potential of Implementing Robotics and Automation in the Context of Large-scale Housing Development for Hong Kong. The consultancy project was structured in four phases. The project duration for the first phase was 18 months. It focused on initial research, conceptual development, exploring appropriate business strategies, construction of a scale mock-up, and planning a roadmap for further development. The second phase of the project is planned to last another 24 months and focuses on developing fully functional construction robots based on the results of the first phase. The duration of the third phase will be approximately 14 months and will focus on system standardization, certification, and training. The fourth phase of the project will consist of organising workshops and an international symposium that will aim to increase public awareness and reinforce international collaboration as part of the dissemination strategy. The fourth phase will last approximately 12 months. At the time of this writing, the first phase of the project has been successfully completed and has laid a firm foundation to carry out the remaining phases.

As the title revealed, the main goal of the project is to discuss the methodological development process for exploring the potential to implement on-site construction robotics (OCR) and automation in the context of public housing construction in Hong Kong. Consequently, the dissertation emphasizes the first phase of the project which documents the completed tasks; demonstrates the research objectives, scope, and methods; evaluates the outcomes of the current project phase, and defines the remaining tasks. In order to provide an overview of the entire project structure, the other phases of the project will be discussed briefly in later chapters. The findings from the dissertation can be used as a guideline to inspire the construction industry globally to initiate and explore innovative, compatible, and feasible solutions to implement OCR in the future.

1.2 Problem definition

The construction industry is one of the top contributors to many country's Gross Domestic Product (GDP) making it one of the largest employment sectors worldwide (Elattar, 2008). Compared to the manufacturing industry, however, the degree of automation in the construction sector lags behind (Wong, Zhang and Lee, 2015). Worldwide, most construction tasks are time-consuming, labour intensive, and often need to be executed in dangerous environments. Since the end of the 1980s, the topic of automation and robotics within the construction industry has become popular yet challenging. Over the years, enthusiasm for this topic has been seen throughout academia, research institutions, and the industry itself. Some researchers consider the implementation of construction robotics and automation the key to solving numerous construction challenges.

All construction projects are complicated and each one has a set of unique requirements and goals due to the intricacy of the project itself as well as various stakeholders specifications and requirements. For instance, public building construction has many sub-tasks and numerous simultaneous processes, such as planning, mobilisation, scheduling, procurement, and controlling. The conditions at a construction site are organized to a certain extent yet are still highly unpredictable. The most versatile elements include material flow, movement of on-site machinery, equipment, and labour. These inconsistent situations vary from the off-site manufacturing facility, however. At the off-site manufacturing production plant, goods are being produced under a more controlled environment: the logistics supply is more organized, job stations are predefined, and, in most cases, human and robot collaboration is limited due to the specific industry safety measure. Given all the moving pieces and intricate processes of construction and construction sites, implementing robotic technology in an on-site construction environment is extremely challenging.

Currently, there is no universally applied definition for the terms "construction automation" or "construction robotics" (Skibiniewski, 2017). The functionality, kinematics, payload, and other specifications of conventional industrial robots are vastly different from construction robots and therefore conventionally used definitions of industrial robotics do not suffice here. The main focus will be on-site robotics technology, of which both construction automation and construction robotics are involved. For the purpose of this dissertation, 'construction automation' will refer to advanced development in changing construction methods and processes, both on-site and off-site, by means of mechanically, teleoperated, semi-autonomous, or fully autonomous construction systems while 'construction robotics' will refer to on-site single or multiple-use construction equipment, enabled by equipping advanced travel platforms, sensors, Information and Communications Technology (ICT), and control systems that can perform one specific or multiple tasks semi- or fully-autonomously, with or without human interaction. To implement construction robotics on-site, foreseeing numerous scepticism, namely around practicality, feasibility, and profitability. it is crucial to understand conventional construction methods, to be aware of which tasks or parts of the process have the potential to be automated and to recognize the degree of automation that needs to be applied. It is also essential to evaluate the human potential versus the robotic capabilities to determine the feasible application and adoption in the construction industry. In addition, because the construction industry has suffered from low margins for a significant period of time, construction robotics needs to both be cost-effective and address a users' priority demands (Yat Hung, Ping Chuen Albert and Chi Man Eddie, 2002).

It is apparent that many companies develop a new product range and development strategies based on existing pivotal products. This type of market-driven strategy creates opportunities for a business, such as incorporating technologies and making transitions from a traditional business setting to a new era driven by the advancement of technological development. Because many construction equipment manufacturers are unfamiliar with the field of robotics, moving from being an emergent technology to a mainstream one proves difficult. As with most technologies, it takes time to leverage and exploit new market potentials, especially when entering unfamiliar territory. Nevertheless, changes in the marketplace can provide competition as well as opportunities (Cravens, Piercy and Prentice, 2000).

Due to the current market structure as well as mainstream academic research, most higher education institutions and universities pay significant attention to market-driven theoretical teaching but often lack interdisciplinary training – students often know very little about subjects outside their own academic domain. For example, architectural and civil engineering students rarely have access to classes about automation and mechanical design, and vice versa. However, in order to conduct research on construction robotics or automation, the researcher must also be equipped with proficient knowledge of traditional construction methods, building technologies, and project management. Moreover, researchers need to be aware of the basics of microelectronics, big data, mechanical design, automation, and manufacturing techniques. These overlapping necessities clarify the need for interdisciplinary teaching and cooperation, generally and show how an important a role interdisciplinary teaching plays in the field of construction robotics, specifically. Another issue slowing down the development of construction automation is low public awareness. The construction industry, the government, and the public sector are not familiar with the topic resulting in insufficient research funding and government incentives for the development of construction automation and robotics.

Hong Kong has many specific issues, requirements, and challenges, such as increasing demand for public housing, increasing property price, an ageing population, and an urgent need to upgrade the overall performance of the construction industry that making it the ideal candidate for a case study. In Hong Kong, as in many other places, the construction industry, the public, research institutions, and most local authorities are unfamiliar with the topics of construction automation and construction robotics. Identifying end-users, specifying stakeholder requirements, and establishing an emergent market chain is therefore essential moving forward. The government, in particular, needs to engage stakeholders in the construction industry to seek innovative methods to solve the aforementioned issues.

As can be seen, there are many obstacles within the construction industry, generally, and in Hong Kong, specifically. These issues demand a comprehensive development guideline that is specifically designed to assist stakeholders in dealing with the implementation of construction automation and robotics on-site. This dissertation will adopt a systematic approach and demonstrate how to prepare such guidelines as well as how to develop a practical application of the guidelines, translating it from a theoretical approach into a near-market-launch stage.

1.3 Research gaps

The introduction of OCR is not a novel approach as its utilization was first recognized in 1983 in Japan, gaining traction in the 1990s when close to 150 single-task robots (STR) were developed. Through research and development (R&D), prototyping, and on-site testing, the early pioneers gained an understanding of the advantages and constraints of applied construction robotic systems over the years (Leslie and Nobuyasu, 1998). In general, STR for on-site application mainly consists of hoisting, fabrication, material logistics, inspection, finishing, mounting, and surveillance. There is still a significant gap between the proposed system and the final market launch, and even though research is being done on the development of those construction robots, it has not been studied sufficiently and often only focuses on the design concept and hardware and software applications. Therefore, many of the previously developed robotic systems have incurred extremely high operational costs, despite, or perhaps because of, the fact they are capable of solving specific technical issues. Many high-quality research papers have been submitted over the years, but the majority of the systems that have been proposed remain as prototypes, which creates a cycle of these systems having higher academic values than applicable market value (Gambao, Hernando and Surdilovic, 2008). Given this, even though around 150 STR have been developed, only very few have been widely used or commercialised because implementing construction robotics is far more complicated than in other industries due to its unpredictable conditions (Leslie and Nobuyasu, 1998). Conducting comprehensive research on the development of OCR in the context of Hong Kong and delivering a system that moves from the conceptual stage to the near-market-launch stage successfully will require addressing the following research gaps.

- Decision support tools on how to tailor-make a range of automation and robotic systems that are feasible for the Hong Kong PHC sector.
  There are limited research topics related to how to implement construction automation and robotics technologies in regard to the PHC in Hong Kong. Evidently, Hong Kong PHC faces an urgent need to improve on-site productivity, construction quality, safety,

and attracting young people to join the construction trade. Implementation of automation and robotics will provide an alternative method to solve these issues. However, there is limited evidence that any guideline was drafted that can be used to assists stakeholders in making critical decisions during the initial research and detailed design stages. Therefore, developing comprehensive guidelines to facilitate decision-makers from the initial research stage to the mock-up building stage as well as providing advice on how to reach the market uptake stage is essential. The guidelines should be developed based on real-case scenarios and then later developed into a universal approach to assist the construction industry as a whole in executing similar types of projects in the future.

- Methodology on how to identify stakeholder's functional and non-functional requirements in regard to on-site construction robotic implementation in the Hong Kong PHC sector.
  There are many stakeholders involved in each phase of a construction project who ensure that the project is on-time, on budget, and satisfies each other's demands. Because individual stakeholders often appear to have different priorities and interests, they frequently seem to be at odds with one another, however, very little research has been conducted on how to determine key stakeholder's functional and non-functional requirements when trying to apply construction automation and robotics, especially during the early development stage. Developing a systematic approach based on the construction context is therefore vital, especially in the early OCR development stages. The proposed approach should be able to identify the key stakeholders and define their requirements, interests, and impact.

- Methodology on how to identify which OCRs have the biggest market potential for Hong Kong PHC sector. To identify which on-site manual tasks need to be automated as well as the appropriate technologies that need to be applied.
  In general, most industrial robots are designed to be operated stationary and instead of the robot moving, the products are passed through the robot station on an assembly line. Because most manufactured products are identical, the industrial robots perform a series of repetitive motion. In addition, most of these tasks are performed in an indoor weatherproof environment where, very often, a Just-in-Time (JIT) and Just-in-Sequence (JIS) logistical strategy are in place. OCR is fundamentally different from an industrial robot, however, due to the complex nature of the construction process. Identifying which conventional on-site construction tasks in the Hong Kong PHC sector that have the potential to be augmented by adopting OCR has not been widely studied. Many design decisions need to be made to ensure the proposed OCR is practical, compatible with existing industry requirements, and marketable. Therefore, an in-depth approach is needed for how to carry out early design decision-making exercises.

- Methodology on how to define the optimum level of automation and define the relationships and trade-offs between automation levels and human factors in specific construction tasks.

Nowadays, industrial robots can perform many tasks in place of a human, however, construction tasks are fundamentally different from the tasks that are performed off-site, in a controlled environment. It is extremely challenging to predict OCR performance and to decide the optimum level of automation or human interaction while the system is under development. Even though there are advanced simulation tools available, it is crucial to obtain tangible performance parameters through testing and operational trials. In the construction context, it is not enough to merely investigate how to use OCR to surpass human limitations but to investigate how to use OCR to complement the human performance. There are very limited resources on how to use engineering rules to contrive the ideal levels of allocation of function to OCR and humans. Therefore, creating a systematic approach specifically for OCR development that can assist the designer in defining what should be automated, the type of automation, and the optimal levels of DOA are of utmost necessity.

- Methodology on how to conduct a Cost-Benefit Analysis (CBA) based on the research outcomes from the CIC project.
  Determining the customer value and the added value of the OCR in an early development stage is a challenging task due to a lack of quantifiable data that is often unavailable before the OCR is fully functional and tested. And because construction practitioners and potential investors are often not familiar with the proposed technologies, an early CBA is important to increase the investor's confidence in the technology and to financially support the development effort. Topics related to CBA, especially focusing on OCR development, are scarce. This dissertation aims to develop a CBA method that can predict the potential benefits as well as the expected payback schedule.

- The development of a new generation of Building Information Models (BIM) that it is compatible with the implementation of OCR.
  Although research has been conducted based on the topic of BIM, very limited research has been carried out regarding implementing BIM technology when introducing robotics and automation technologies in an on-site construction project. There are a number of fundamental changes in how to gather, process, and distribute construction data when OCR is involved. When planning to adopt OCR, a new information management system is needed that can handle large volumes of heterogeneous data as well as enhance information acquisition and integration while providing real-time data sharing among all key stakeholders (Pan, Langosch and Bock, 2017).

1.4 Research objectives

This research aims to develop comprehensive guidelines that function as a decision-making tool to help key stakeholders when considering adopting automation or robotic technologies on construction sites, particularly when implementing OCR to enhance a specific range of on-site tasks. The guidelines will be formulated based on the consultancy project commissioned by the CIC in Hong Kong. Although the context of the study is concentrated on the Hong Kong PHC sector, the methodology developed can be considered as a universal approach that can assist the construction industry as a whole in executing a similar type of project in the future. The proposed guidelines have four specific objectives. First, providing a holistic approach that makes the relevant stakeholders aware of the existing challenges faced by the construction industry as well as offering feasible construction automation or robotic solutions. Second, demonstrating a variety of methods that can assist the key stakeholders in identifying their priority requirements regarding how to adopt automation and robotic technologies on-site. Third, using the guidelines to provide a systematic approach that offers decision-making parameters that need to be taken into consideration when designing and adopting OCR and then recommending the key performance indicator (KPI) that is the most helpful for the development of the system and ultimately narrowing down the overall development scope. Fourth, using the guidelines to provide an in-depth process that demonstrates how to tailor-make OCR that is functionally, economically, and institutionally viable for the client. Last, exploring current market trends to propose adequate business models that are suitable for market adoption as well as market uptake potential.

1.5 Research questions

Addressing the following research questions will help fulfil the above research gaps and achieve the aforementioned objectives:

1. What type of challenges is the Hong Kong PHC sector facing?
2. What are the characteristics possessed by the Hong Kong construction sector that support OCR implementation?
3. Which existing on-site construction tasks can be potentially optimised by adopting construction automation and robotic technologies?
4. How can keys stakeholders and their requirements in the context of OCR development be identified?
5. How can the optimum allocation of functions between man and machine, Degree of Freedom (DOF), sensory technologies, hardware, software application and Degree of Automation (DOA) when developing OCR be identified?
6. How can OCR technologies to the conventional construction industry be introduced?
7. What type of KPIs associated with OCR should be verified during the system development stage?
8. What is the appropriate business model for the proposed technologies?
9. How can the value of the OCR in an early stage of the project be measured?
10. What is the purpose of the guidelines and how will they be used?

1.6 Research scope

1) Hong Kong PHC sector

   This research focuses on how to solve the current challenges that are faced by the Hong Kong PHC sector by implementing construction robotic and automation strategies. Because of a clear geographical boundary for the study and the type of the industry being studied, this study offers industry-specific and focused approaches. The investigations will solely surround the on-site tasks, the involved stakeholders, and the social and economic impacts of the identified industry, but will not include commercialised residential building, commercial building, public building, and industrial building sectors as they are outside the research scope. The detailed study of the final implementation, government policy, legislation, and financial acquisition are also beyond the scope of this research.

2) Building typology

   The research focuses exclusively on high-rise public residential buildings. The selected on-site case study buildings are located at Ngan Kwong Wan Road in Mui Wo, Hong Kong. The selected buildings, in terms of their design features, construction methods, and managerial strategies are of a typical style of public housing building typology in Hong Kong. In addition, the research focuses on aboveground construction, such as the foundation piling. Underground services installation will not be discussed.

3) Construction automation and robotic technology

   The research focuses on construction automation and robotic technologies that can be adapted to assist on-site construction tasks. Off-site construction technologies such as prefabrication will only be introduced briefly but are again outside the scope of the research. The guidelines of selection, concept development, detailed design, building mock-up, and dissemination of the proposed OCR will establish the core development initiatives. Extensive robotics programming, detailed electrical and pneumatic hardware final system integration and system optimisation are also beyond the scope of this research.

4) Project reference

   The research is primarily based on the first phase of the consultancy project commissioned by the CIC in Hong Kong and covers from the initial research stage to the mock-up demonstration stage. The research targets and objectives in the follow-up phases will be described briefly.

1.7 Methods

The consultancy project represented an opportunity to discover what kind of methods needed to be developed to implement OCR in the Hong Kong PHC sector. In order to systematically address the research questions, and to fulfil the research gaps, the project has been divided into six stages. The first phase consists of the initial research, a literature review, the preselection, and proposition of using case scenarios. The second stage includes an online survey, questionnaires, and an on-site visit. The third stage is the co-creation workshops. The fourth stage is concept development and detailed design of the proposed system. The fifth stage includes the construction of the mock-up and a discussion of the dissemination and exploitation strategies. The final stage is developing a roadmap that provides a guideline on how to execute the remaining project and finally bringing the proposed OCR to the market launch stage.

1.7.1 Initial research and requirement identification

The initial research aims to evaluate the current situation in the Hong Kong PHC sector including the existing construction methods, challenges, policies, labour market analysis, and potential technology transfers, see chapter 1 for more detail on this. An overview of the history and the current trends of construction automation and robotics will be examined. A comprehensive literature review will also be carried out and covers journals, reports, books, conference proceedings, theses, and dissertations that are related to the research questions. As part of the identification tasks, stakeholder analysis and initial stakeholder requirements identification will be carried out. The purpose of the initial research is to gain a background understanding of the current Hong Kong PHC sector, evaluate the weaknesses and strengths, enhance awareness of the proposed strategies, define key stakeholder attributes, and make sure the research direction is correct (Pan, Wen et al., 2018).

1.7.2 Online survey and the on-site visit

Following the initial research of a series of automation and robotic technologies that had been suggested to the PHC sector, an online survey was conducted to investigate the feedback from the selected stakeholders and to determine the feasibility, compatibility, and practicality of the proposed technologies. After the online survey, the author conducted a three-week on-site visit at one of the on-going construction sites in Hong Kong. The on-site visit focused on evaluating the existing PHC working conditions, labour welfare, health and safety, insurance policies, and severe weather warning protocols. Using both top-down and bottom-up methods, on-site challenges were analysed and opportunities were explored for construction automation and robotics adoption. The main outcome of the online survey and on-site visit was to determine which task or part of the task could be improved by implementing automation and robotics (Pan, Wen et al., 2018).

1.7.3 Co-creation workshop

After the online survey and on-site visit, the two days workshops were organised. The objectives of the workshops were to gain practical feedback from industry experts. The first group of objectives were evaluating market drivers, technical feasibilities, and barriers to the implementation of the proposed technologies. The second group of objectives were identifying product functions, working processes, and the compatibility of the proposed technologies. The third group of objectives were identifying the functional and non-functional requirements as well as strategically mapping out plans and actions for the near feature. The workshops were an important milestone of the consultancy project and the collected data was used to formulate the roadmap on adopting on-site construction technologies in Hong Kong. In addition, a number of KPIs were identified that assisted the project team in narrowing down the research scope and determining a more focused research direction (Pan, Wen *et al.*, 2018).

1.7.4 Concept development and initial design

Base on the outcomes and feedback from the initial research, the online survey, the on-site visit, and the co-creation workshops, the project team was able to decide which OCR would be further developed. The development goals were defined by stakeholder feedback and veritable terms were established to help the project team initiate system specifications, performance criteria, feasibility, operational safety, and a working process. After quantifiable design goals were set, conceptual designs were carried out to analyse the case study building and to determine the suitable level of allocation of functions between man and machine, DOF, sensory technologies, hardware application, software application, and DOA. The conceptual designs were also used to draft the composition of the proposed design and was initially digitalised using design software. The conceptual design was then materialised by producing scaled table-sized physical prototypes, which offered a comparable representation of the critical design features of the OCR, such as DOF, kinematics, and working process. The conceptual design was finalised by studying off-the-shelf products, scaling up strategies, potential business models, and practicality regarding the PHC in Hong Kong.

1.7.5 Mock-up building and demonstration

Based on the detailed designs, a 1:2-scale working OCR mock-up was designed and produced as part of the OCR development process. The main purpose of the mock-up was to demonstrate the main function of the proposed OCR, enable the design team to refine the design, and gain feedback from the stakeholders. Later the mock-up was shipped to Hong Kong and featured at the Construction Innovation and Technology Application Centre (CITAC). The mock-up is a valuable dissemination tool for both br^2 and the CIC to promote the concept to the Hong Kong public, generally, and the construction industry, more specifically. Furthermore, the mock-up is an important stepping-stone toward full system implementation, lab testing, pilot projects, and eventually commercialization.

1.7.6 Economic performance estimation

The economic performance of the proposed OCR was evaluated through CBA and cost-effectiveness analysis (CEA). The methods were developed based on the CIC project and the relevant data was collected through stakeholder analysis, an on-site case study, the co-creation workshops, the initial design, dissemination, and market positioning. A value-based price method was adopted through CBA, focusing on monetary estimation and incremental costs while incremental benefits were evaluated through CEA, concentrating on the non-monetary factors. In Section 4.4, the detailed methods are illustrated.

1.7.7 Roadmap and guidelines

The roadmap was developed based on the data collected from Hong Kong PHC contractors, local authorities, consultants, architects, academics, and Non-Governmental Organizations (NGOs), see chapter 6 for more detail. The roadmap aims to give an introduction of construction automation and robotic systems and to identify the technology drivers, facilitators, and responsibilities of all stakeholders. The guideline provides and illustrates the methods that will be used in resolving technological, social, economic, and political factors. It also attempts to detect unforeseen barriers, feasible solutions, and recommendations for action plans. In addition, the guidelines provide a detailed task breakdown with corresponding recommendations on each task. The guidelines also demonstrate a systematic method that can support decision-making for developing OCR, from the conceptual to the demonstration phase (Pan, Wen *et al.*, 2018).

1.8 Dissertation outline

This dissertation provides a systematic development of a methodological approach for how to identify which existing construction tasks can be augmented by adopting automation and robotic technologies as well as developing methods for how to follow the proposed guidelines to develop a commercial application. The proposed methodological approach will be designed based on the CIC project and focus on the first phase of the project that covers the initial research stage to the mock-up demonstration stage. The dissertation structure is shown in Figure 1, and the brief content of each chapter is outlined below.

Chapter 1 - Introduction

This chapter provided the background, problems, research gaps, and research objectives of the research project. The research questions, scope, and methods were highlighted.

Chapter 2 - Background and related work

This chapter features detailed background information and discusses the challenges faced by the Hong Kong construction industry with a focus on the PHC sector. The introduction of construction automation and robotics is demonstrated while questioning why and how to automate. A comparison of manufacturing and construction is evaluated. State-of-the-art OCR technologies are introduced, focusing on commercialized systems, and the obstacles faced by the construction industry when adopting OCR technology are evaluated.

Chapter 3 - Methodical development based on the Hong Kong case study

This chapter provides the main content of the CIC project. It covers eight sub-topics, including stakeholder analyses and initial requirement identification, online surveys, the on-site visit, the co-creation workshop, the initial system design, the system development process and iterative planning, and conceptual prototyping and initial dissemination. The major part of the comprehensive methodological approach is developed in this chapter.

Chapter 4 - Business strategy development

This chapter presents the proposed business strategy that defines target markets and key customers, conducts a cost-based analysis, and evaluates the barriers and drivers that have implications for potential market uptake and business strategy development of the proposed OCR.

Chapter 5 - Evaluation of the result

This chapter illustrates how to identify system performance indicators while the system is still under development. Evaluation methods are proposed and the critical tasks involved when attempting to bring the proposed OCR closer to the market launch stage are explored.

Chapter 6 - Roadmap and guidelines development

This chapter provides a generic roadmap that lays a foundation for developing the guidelines, divided into eleven stages. Instrumental recommendations on how to conduct each project stage are advised and the lessons learned from the CIC project are examined and serve as a reference for undertaking future projects.

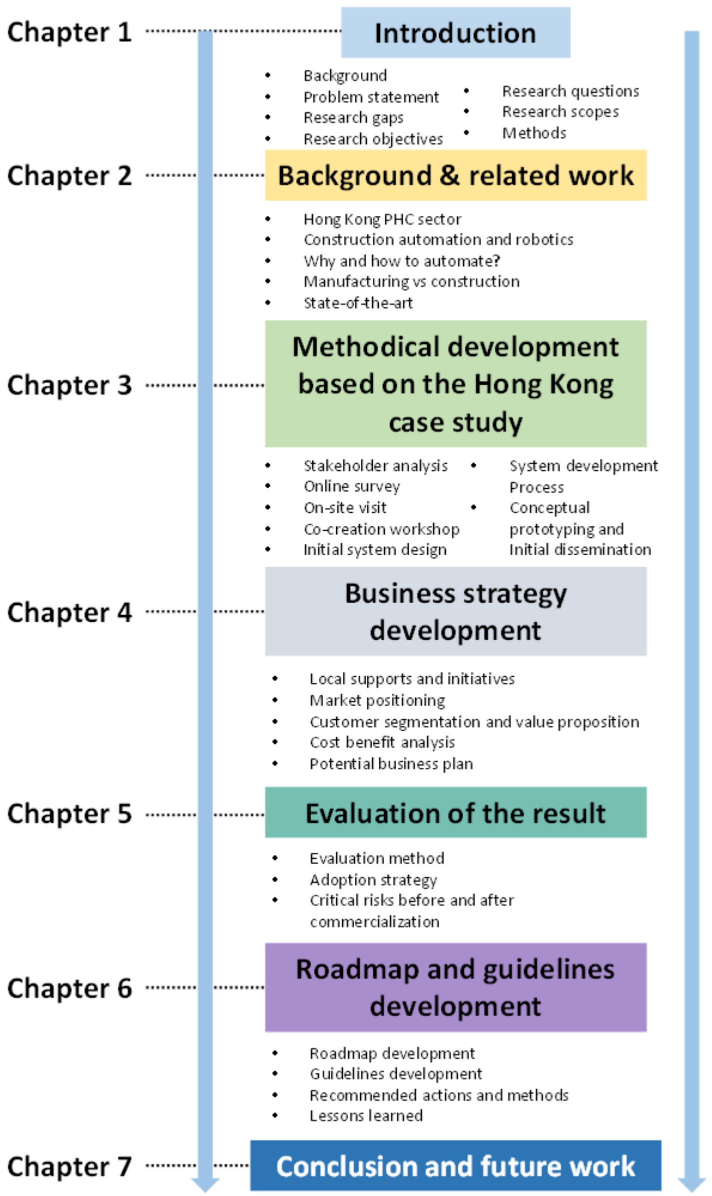


Figure 1: Dissertation outline.

2 Background and related work

The dissertation has chosen Hong Kong as a geographic boundary and conducted a comprehensive study on the existing Hong Kong construction industry and the Hong Kong public housing construction sector. In this section, the focus lies on identifying the challenges faced by Hong Kong construction industry, analyzing the unique circumstances in Hong Kong, evaluating the state of art technologies in the construction robotics field, while additionally looking into the challenges when adopting automation and robotics in the conventional construction industry. To determine if automation and robotics can be an alternative approach to solve the identified issues, the considerations need also to be taken into account across the entire value chain. The chapter will lay down a foundation that assists the key research task, and ultimately will provide scientific backup in proposing systematic methods for answering the identified research questions.

2.1 A brief introduction of Hong Kong

Hong Kong became a Special Administrative Region (HKSAR) of the People's Republic of China (PRC) on July 1st 1997. The event is often referred to as the handover of Hong Kong, which marked the end of a century and a half of the British colonial rule. Hong Kong is situated at the southern tip of the mainland China, with a total area of 1104 km^2, which consists of three main islands: Kowloon, Hong Kong, and New Territories see Figure 2.

Figure 2: Victoria Peak, source: (Wen Pan).

Hong Kong has a population density of 6,300 people per square kilometre, and a total population of 7.4 million. The official language in Hong Kong is Chinese, mainly Cantonese, and English. The climate in Hong Kong is humid sub-tropical, with hot and humid summers along with regularly occurring typhoons. The winter is rather mild with fewer rainfalls. Hong

Kong is one of the largest financial centres in the world; after rapid industrialization in the 1950s, Hong Kong's manufacturing industry experienced significant growth. ('A modern history of Hong Kong', 2004). The manufacturing sector starts to decline in the 1970s due to increased salaries and the cost of the land. Since then Hong Kong has benefited from the "Open Door" policy also known as the PRC's economic reforms, which aided its economy in steady growth after injection of heavy investments in the Pearl River Delta Metropolitan Region (PRD). Since 1997, Hong Kong has emerged as the centre for high value-added services. On top of this, Hong Kong also serves as a doorway to PRC and the rest of the world (Shih and Jones, 2014).

2.2 Hong Kong construction sector

The construction industry is one of the main contributors to Hong Kong's rapid economic growth. Based on the forecast by the CIC in 2017, the annual construction expenditure will exceed 250 billion Hong Kong Dollar (HK$) in the next five years. This is equivalent of approximately 5% of the Gross Domestic Product (GDP) (CIC, 2019). It is expected the output value of construction works conducted by main contractors in Hong Kong will increase from HK$176.6 billion in 2017 to HK$206.8 billion in 2021 with Compound annual growth rate (CAGR) approximately of 4%. This rapid growth is fuelled by the HKSAR government's initiatives to increase public housing supply, land acquisition for private housing, commercial development and other crucial infrastructure project according to the statistics data provided by Research Office Legislative Council Secretariat. Since 2018, there have been a total of 1489 construction sites in Hong Kong, with a 46.8% increase of that in 2008. The numbers of public construction sites have increased faster than private sites. However, private sites still dominate the entire construction volume by 59% in 2018. In terms of construction costs, Hong Kong has been rated the third most expensive place to build, after New York and San Francisco, and with the highest construction cost in Asia (Research Office Legislative Council Secretariat, 2018).

2.2.1 Local Vision

The Hong Kong construction industry has a direct impact on every other aspect of life in Hong Kong society. Changes in demographics, risen demand for housing, and in a broad sense, the requirement for a better life for the people of Hong Kong has become the priority task for the HKSAR government. How to face those challenges and search for feasible solutions are essential to the social and economic advancement of Hong Kong. In 2012, a roadmap called Vision 2020 that offered a guideline for the construction industry on how to address critical issues and to meet the expectation of the general public has been outlined by the Hong Kong Construction Association (HKCA) and Construction Industry Group (CIG) (Bussiness Environment Council, 2013).

The Hong Kong construction industry is composed of a range of stakeholders, for example, architects, developers, contractor, public authorities, city planners, Building Department (BD), environmentalists, suppliers, institutions, labour unions, bankers and economists. The proposed vision aims to focus on the tasks that have been already initiated to support on-going activities by understanding individual requirements from the stakeholders (To, 2016). The Vision 2020 addresses five strategy areas, which include 1) Safety, health and quality of life, 2) Preservation of the environment, 3) Procurement processes, 4) Productivity, 5) Viable construction industry. The five strategies were introduced along with specific industry priorities in order to reflect the diverse interests of the stakeholders (China Daily, 2012). The identified industry priorities are shown as below in Table 1.

Table 1: Hong Kong industry priorities, source: (Hong Kong Construction Association, 2012).

Hong Kong Industry Priorities				
Health, Safety and concern for all impacted by construction activities	Minimise the impact on the existing physical environment and reduce energy levels across the project life cycle	Develop integrated procurement practices that are equitable to all in the supply chain	Optimise the human and technical resources through fair reward and innovative solutions	Secure the future of Hong Kong's built environment through long-term visionary planning

Achieving the goal mentioned in vision 2020 will require a well-defined collaborative industry development plan. Now, the CIC is focused on affiliates with experts from in and outside the industry attempting to solve the challenges through cross-disciplinary collaboration, training, legislation, and innovation. There are some other obstacles that have direct and indirect effects on transforming the Hong Kong construction industry. Notably, Hong Kong faces high costs of construction, land and labour shortage, health and safety constraints, and productivity deterioration. The following section will provide a detailed analysis of the topics (Hong Kong Construction Association, 2012).

2.2.2 Cost escalation

Generally, in Hong Kong, labour contributes approximately 25% to 35% of total construction project cost, while materials cost up to 45% of the total project cost. According to the HKSAR Census and Statistics Department (C&SD) data, there was approximately 48.6% increase in composite labour wages for building contracts from 2013 to 2018. In addition, there are some other factors that drive up construction cost besides labour, and material cost (Rowlinson, 2014). The main contributors to cost escalation can be summarized as below:

- Material cost: Most of the construction material prices have increased dramatically in the last decade. This is due to the high dependency of imported materials from mainland China or abroad. The fluctuation of exchange rates and inflation rates are also influenced by the shifts of the internal and international economic environment, which could also contribute to increases in cost.
- Labour cost: The daily wage of labour increased significantly in recent years, especially in the specific trade that experiences skill shortages. This trend is also contributed by a general labour shortage in the construction industry as a whole. The construction industry appears to be less attractive to the younger generation so that the industry has to continue offering higher wages in order to attract younger recruits.
- Health and safety: To improve on-site safety is an important agenda for the construction industry, due to severe consequences and compensation rates of related occupational

injury or fatality case. The initiatives of improving on-site health and safety will contribute to the increase of the total contract cost.

- Environmental considerations: The construction activities are energy and carbon-intensive. The construction waste reaches approximately 25% of the daily disposal in Hong Kong (Wong, Zhang and Lee, 2015). The government requests the contractor to carry out environmentally friendly approaches when it comes to construction methods and waste disposal. This type of initiatives will increase the total contract cost incrementally.
- Procurement system: Different procurement strategies may also influence the costs of the project, such as to use a collaborative form of contract and reduction in claims.
- Guideline and certification: As the industry is moving towards a well-regulated, safe, and transparent industry, the efforts spent on improving the existing regulation, certification system, safety, and workers welfare will contribute to the overall cost of the total contract cost.
- Contractual method: High risk is caused by the uncertainty of the contract leads to input higher liability insurance into the bidding price.
- Tender costs & bid preparation: Caused by complicated and heavy administration works during the tendering and bid preparation period. To make the situation worse, short preparation time will increase the risk premium and the contract cost.

2.2.3 Land shortage

Land scarcity is one of the typical issues faced by Hong Kong escalated by overcrowding, population growth, and lack of land for housing development, with economic prosperity becoming one of the major concerns for the HKSAR government. The society experiences issues associated with the impacts of land shortage. The soaring property and rental prices, yet small, inadequate living conditions, and the increasing gap between the rich and the poor is directly attributed to the limited land supply. Hong Kong has a mountainous topography with a total land area of 1104 km^2, approximately 270 km^2 is a built-up area with 841 km^2 non-developed area, respectively. According to the Planning Department of Hong Kong, out of the limited build-up areas, housing development land only takes up to 3.7%, with 2.3% for private housing construction and 1.4% for public housing development. C&SD estimate the population and household of Hong Kong will continue to increase in the coming years. Due to demographic changes, the size of the household decreased, but the total number will increase from 2.51 million in 2016 to 2.97 million in 2049 (Task Force on Land Supply, 2018). Therefore, to ensure adequate land are supplied to meet the development need and to justify the population, economic growth becomes ever more challenging.

Several proposals aim to improve the efficiency of land use and increase land supply. The Transport and Housing Bureau launched a Long Term Housing Strategy (LTHS) in 2012 (Transport and Housing Bureau, 2014). The strategy indicates long-term development plans for the next decade, which is focused on the supply of public rental housing (PRH). Key recommendations were suggested in regards to enhancing government effort on solving supply-demand imbalance, housing supply targets, setting up priority groups, and working relations with Urban Renewal Authority (URA) in providing additional land for public housing (Gurran and Bramley, 2017).

The Development Bureau, the Civil Engineering and Development Department (CEDD) and the Planning Department commenced a study on "Enhancing Land Supply Strategy, which focuses on reclamation outside Victoria Harbour, and Rock Cavern Development (Civil Engineering Development Department, 2019). In 2017, the planning department in Hong Kong has made a great effort in securing land supply and expansion to New Development Areas (NDAs). In total, 210 potential housing sites were discussed over the on-going land use reviews. In 2017, the planning department has completed statutory rezoning procedures for 104 sites, which supply approximately 122,900 housing units. In addition, another 41 sites, equivalent to 74,100 housing units already began their statutory rezoning procedures (Planning department, 2018). In order to complete those initiatives, the construction industry has to improve the existing construction productivity, by considering those targets as motivation to drive innovation, improving construction technologies, and labour skills.

2.2.4 Labour and skills shortage

Hong Kong faces a growing and ageing population and a declining workforce. According to the C&SD projections, the Hong Kong population will continue to grow and reach its peak at approximately 8.22 million in 2043. Despite the growing numbers of the total population, a growing trend indicates the population is ageing fast. Based on the government perdition, the portion of the population over 65 years old will increase significantly from about 15% in 2014 to almost 36% by 2064. The population over 85 years old will increase from 2.2% in 2014 to approximately 10.1% by 2064. The ageing population also means a decrease of the active labour force, declining productivity, and higher labour costs, which will cause serious impacts on social and economic situations in Hong Kong (Planning department, 2018).

Between 1998 and 2007, the Hong Kong construction industry suffered a huge depression due to the global economic crisis. Many skilled construction workers were leaving the industry and working in other sectors. Since 2008, some major infrastructure projects were taken place, and both demands for new construction in the private construction sector as well as the public sector are accelerating. The growing demand has intensified labour and skill shortage in the construction industry. In dealing with this, the CIC has established many initiatives by providing enhanced training programs and offering more incentives that are attractive to potential recruits. Experienced and qualified trade instructors will train and pass on the specific trade's skills to the new recruits under the CIC's training centres. Currently, there are three training campuses available, which include Kowloon Bay Campus, Sheung Shui Campus, and Kwai Chung Campus. The new recruits will be permitted to work in the specific trade once the training is successfully completed and the trade test is passed. The tasks for which the training centre is unable to provide practical training, for example, in case of tunnel boring machine operator, a dedicated training scheme was offered by the CIC that was working closely with the contractors. Under this training scheme, the contractor can employ prospective recruits and conduct training under the CIC's supervision. Despite these efforts, Hong Kong construction sector is still facing difficulties in replenishing the workforce and the existing workforce is ageing rapidly (Paul H K Ho, 2016).

According to the Construction Workers' Registration System (CWRC) from the CIC, see Table 2, the total number of construction workers who successfully registered as in 2009 is 361,398. In which 160,752 are Registered General Worker (RGW), 24,444 are Registered Semi-skilled Worker (RSS), 2764 are Registered Semi-skilled Worker (Provisional) (RSS (p)), 160,634 Registered Skilled Worker (RSW), and 12,804 Registered Skilled Worker (Provisional) (RSW (P)) (CIC, 2019).

Table 2: Total number of the valid registered worker in designated trades from 2009 to 2018.

Total Number of Valid Registered Workers in Designated Trades as at 31/12/2009					
RGW	RSS	RSS(P)	RSW	RSW(P)	Total
160,752	24,444	2764	160,634	12,804	**361,398**
Total Number of Valid Registered Workers in Designated Trades up to 28/02/2018					
RGW	RSS	RSS(P)	RSW	RSW(P)	Total
234,744	26,911	1	202,713	1188	**465,557**
Source: From the CIC Registered Workers in Designated Trades, 2009 and 2018					

In comparison, the total registered workers are 465,557, with 234,744 RGW, 26,911 RSS, 1 RSS (P), 202,713 (RSW), and 1188 RSW (P). There was an increase of about 104,159 in registered workers between 2009 and 2018. The amount of registered workers does not represent the total number of workers active on-site. The CIC reports that the current active workers are 330,000 (CIC, 2019). Moreover, C&SD provides an analysis of the registered labour who is not engaged in construction works and the reason why. The analysis covers a 12-month period from the beginning of January to the end of December 2017, see Table 3.

Table 3: The numbers of the registered worker who is not working in 2017.

The numbers of the registered worker who is not working from 01/01/2017 to 31/12/2017								
Reason	RSW	Rate	R SS	R ate	RGW	Rate	Total worker	Rate
Retired	26,750	70.98%	1750	40.37%	22,436	36.48%	50,891	49.21%
Cannot find a job	7309	19.39%	1816	43.01%	8069	13.12%	17,194	16.63%
Age related issues	908	2.41%	56	1.32%	6003	9.76%	6967	6.74%
Never worked in the construction sector even though has the skills	48	0.13%	33	0.79%	5609	9.12%	5690	5.50%
Health/Family issues	2388	6.34%	591	13.98%	7577	12.32%	10,556	10.21%
Not suitable/ lost interests	287	0.76%	22	0.53%	11809	19.20%	12,118	11.72%
Source: From C&SD registered worker analysis from 01/01/2017 to 12/31/2017								

The statistics indicate the prime reason that the registered worker is no longer engaged in the construction task is retirement. This data further supports the notion that the Hong Kong construction industry is ageing fast.

According to the latest released 'Construction Expenditure Forecast and Manpower Forecast' by the CIC, the construction as a whole suffers a shortage of 5,000 to 10,000 skilled workers. The forecasts were generated based on the overall construction expenditure volume in both private and public sectors, along with the number of registered workers, their skill level, and age distribution. When comparing the numbers of workers in each skill set by age, the impact of an ageing workforce is somewhat obvious. As shown in Table 4, according to C&SD analysis in 2017, the registered workers in RSW, RSS, and RGW between ages 50 and 59 years old were 115,375, which is equivalent to 25.83% of the total labour force. In contrast, there were 1220 workers registered in all skill sets who were below 20 years old, which is merely 0.27% of the total workforce. Furthermore, the data demonstrated that registered workers between 40 and 49 years old and over 60 years old comprise 23.71% and 17.16% of the total workforce, respectively. As a result, within the current construction workforce, there were 66.70% of the workers over 40 years of age (CIC, 2019).

Table 4: Registered worker analysis in 2017.

Age	RSW	Rate	RSS	Rate	RGW	Rate	Total worker	Rate
< 20	5	0.4 1%	143	11.72%	1072	87.87%	1220	0.27%
20 -29	3803	5.54%	8651	12.60%	56,223	81.87%	68,677	15.37%
30 -39	27,652	35.05%	7329	9.29%	43,919	55.66%	78,900	17.66%
40 -49	49,191	46.44%	4787	4.52%	51,946	49.04%	105,924	23.71%
50 - 59	63,543	55.27%	3439	2.98%	48,393	41.94%	115,375	25.83%
60 >	43,127	56.27%	2245	2.93%	31,273	40.80%	76,645	17.16%
Total	187,321	41.93%	26594	5.95%	232,826	52.12%	**446,741**	100.00%
Source: From C&SD registered worker analysis from 01/01/2017 to 12/31/2017								

The most significant challenge faced by the industry is the exceptional amount of new projects scheduled in the coming years. The projected construction work include LTHS for the public domain, Hospital development program, Railway Development Strategy (RDS), Airport expansion program, Climate Action Plan 2030, Brown filed development and Land reclamation projects.

The increasing volume of construction will increase pressure and potential risks on the current construction labour supply. To make the situation worse, the CIC has conducted an industry analysis, aiming to identify the number of workers, who are lacking in the specific skill category (CIC, 2018). The estimated labour shortages on specific skill category from 2018 to 2022 are shown in Table 5.

Table 5: Skilled construction workers forecast from 2018 to 2022.

#	Skill category	2018	2019	2020	2021	2022
1	Bar Bender & Fixer	501-1,000	≤500			
2	Concrete Finisher	≤500	≤500	≤500	501-1,000	501-1,000
3	Plumber	501-1,000	501-1,000	501-1,000	501-1,000	501-1,000
4	Scaffolder	≤500	≤500	≤500	≤500	501-1,000
5	Carpenter	≤500	≤500	≤500	501-1,000	501-1,000
6	Plant & Equipment Operator	≤500	≤500	≤500	≤500	≤500

7	General Welder	≤500	≤500	501-1,000	501-1,000	501-1,000
8	Metal Worker	501-1,000	501-1,000	501-1,000	501-1,000	501-1,000
9	Glazier	≤500	≤500	≤500	≤500	≤500
10	Plasterer Terrazzo & Granolithic Worker	501-1,000	501-1,000	501-1,000	1,001-1,500	1,001-1,500
11	Electrical Fitter	≤500	≤500	1,001-1,500	1,501-2,000	1,501-2,000
12	Refrigeration/ AC/Ventilation Mechanic	501-1,000	501-1,000	501-1,000	501-1,000	501-1,000
13	Fire Service Mechanic	≤500	≤500	≤500	≤500	501-1,000
14	Lift and Escalator mechanic	501-1,000	501-1,000	501-1,000	501-1,000	501-1,000
Source: From the CIC construction worker shortage forecast from 2018 to 2022						

In order to solve the increasing labour shortage issue, there were eight response strategies suggested by researchers, which are demonstrated as follows.

1. Increase workers' wages and benefits:
   In general, increasing workers' wages and benefits package will result in an increase of labour supply (Borjas, J, 2010), due to the low-profit margins in the construction industry, plus high risk, and high demanding physical activities often associated with construction work (Akintoye and Skitmore, 1991). This makes the industry less attractive to prospective recruits, especially younger workers. However, offering competitive wages can boost prospective workers' confidence in joining the industry, but at the same time will potentially increase construction cost. It is important that contractors association, the Hong Kong Confederation of Trade Unions (HKCTU), and the client work together to find a common ground, where mutual benefit can be accrued to all sides (Ho, 2016).

2. Import migrant workers:
   As Hong Kong experiences rapid demographic change, the local labour supply is not sufficient in order to replenish the labour stock. Increasing wages are not going to tackle the entire issue. Another direct solution is to import foreign skilled workers. Some may ask, why not import workers from mainland China? This is because mainland Chinese does not automatically qualify to seek employment or invest in Hong Kong. For those mainland Chinese who would like to take employment in Hong Kong need to apply for a working visa from the immigration department. The Admission Scheme for Mainland Talents and Professionals (ASMTP) was set up to attract mainland talents, yet the exact data of how many mainland workers working for the construction industry is unknown. In contrast, according to the Hong Kong Labour Department, there is an increased number of Hong Kong residents taking employment opportunities triggered by recent economic growth. In addition, there is the Supplementary Labour Scheme (SLS) that allows local employers with difficulties in finding suitably skilled staff locally to recruit migrant workers. The local employers must prioritize local work and make a genuine effort in training them before considering employing a foreign worker. It is noticeable,

many training courses offered by the Hong Kong Institute of Construction (HKIC) are taught in English. The applications involving the enhancement measures approved under SLS with a breakdown by 26 manpower shortage trades indicates there were 485 imported workers that applied for the scheme in the year 2015 and 405 of the applications were accepted (Hong Kong Labour Department, 2019).

3. Increase training quality and incentives:
   To provide high quality and consistent training is essential for the construction industry to acquire new skills and to achieve long-term sustainable growth. The CIC is the main organisation that offers extensive training for the construction industry. The Contractor Cooperative Training Scheme (CCTS) is a "First-hire-then-train" scheme, which is designed to allow the contractor to employ new recruit then provide on-the-job training with CIC's supervision. This training scheme is being considered as part of the trial work period, due to the prospective recruits being exposed to on-site working experience first-hand and if the new recruits cannot stand the condition then they will drop out of the training in an early stage (Hong Kong Institute of Construction, 2019). Therefore, resources or training efforts will not be wasted. In addition, the CIC has implemented the Enhanced Construction Manpower Training Scheme (ECMTS), which allows the successful trainee to receive sufficient amount of allowance during the training period, also to secure a stable income from the prospective employer (Hong Kong Institute of Construction, 2017).

4. Adopting innovative construction technologies
   Overcoming labour shortage and productivity issues also require the implementation of new construction technologies. The Hong Kong Housing Authority (HKHA) has been adopting advanced prefabrication construction systems for the public housing project. Now, Modular Integrated Construction (MiC) has been promoted by CIC as the potential technology that can release labour pressure. From the academic level, The University of Hong Kong has established the Robotics laboratory for working on specialized construction robots that can replace human working under dangerous conditions. The Hong Kong University of Science and Technology (HKUST) has been working on a robotic application for off-site metal components fabrication (Wong, Zhang and Lee, 2015). To materialize new technology adaptation, the construction industry has to face two fundamental issues. First, the industry is still very conventional, which may not support the proposed technology. Second, adopting new technology takes a considerable amount of money and time, and the contractor or the end-user do not necessarily have the financial incentives to implement proposed technologies. Unless there will be the direct financial gain or the government incentive, the contractor will only adopt technologies that are cost-effective and when as required. Positively, the Financial Secretary has launched HK$1 billion Construction Innovation and Technology Fund (CITF) to encourage innovative adoption of advanced construction technologies and methods. The CIC has been commissioned as an implementation partner (CIC, 2019). In addition, the Innovation and Technology Commission has administered the Innovation and Technology Fund (ITF) that aims to assist local

companies to engage in technological upgrades and increase the competitiveness of the Hong Kong economy. Based on the statistics, 9038 projects currently have been approved by ITF by the end of 2018 (Innovation and Technology Commission, 2019).

5. Improving working conditions
   Construction activities are still labour intensive, risky and the on-site working condition is not as attractive as other sectors. One way to improve the working condition and safety is to educate and increase the worker's and contractor's safety awareness throughout the safety training program. The management team should ensure the site is well maintained, clean, and front line works are equipped with uniformed safety wares. The government should reinforce any safety-related regulations, in parallel, to increase rewards for the contractor achieving safety targets (CIC, 2012). The detailed discussion regarding health and safety will be illustrated in the next section.

6. Enhance multiple skills training
   When workers have acquired over a variety of skills, then the multi-skill can transfer to different trade fields, and fill up the existing labour gaps (Haas *et al.*, 2001). When visiting KUKA robotic company factory in Augsburg, Germany, it was interesting to notice that their workers have obtained multiple skills under in-house training. Their management can allocate the worker in different workstations when necessary. For the workers, they feel more motivated to carry out different types of tasks and feel less dull than consistently working on a repetitive task. The contractor should encourage workers to take up alternative training and work on different trades, of course, an incentive should be offered to cover additional expenditure, and any productivity gain should be awarded.

2.2.5 Health and safety

As mentioned earlier, Hong Kong has been experiencing a huge increase in construction output, high construction cost and severe labour shortage. Followed by the aforementioned issues and increasing construction demand, construction safety is still a great concern. Even though a great amount of effort has been made to improve health and safety, construction occupational injuries still account for approximately 8.5% of project cost (Steve Rowlinson et al., 2009). Several initiatives were taken in order to improve construction operational safety. They can be described as follow:

- Constitutional: The Occupational Safety and Health Ordinance has given a guideline to the industry practitioners on how to ensure good a standard of health and safety in practices, to prescribe measures that will improve employees health and standards and working environments as a whole.
- Financial: The Pay for Safety Scheme (PFSS) is one of the key initiatives for improving construction safety. The PFSS has been recommended by CIC and wildly adopted by the industry. An incentive will be awarded to the contractor or the responsible person who made great a contribution to improve construction safety.

- Procedural: This includes on-site inspections of various trades and stages of construction work. It mainly compresses the PASS assessments adopted by the HKHA.
- Punitive-administrative: Any contractor that breaches the health safety regulation, which leads to serious occupational injuries or death, depending on the cause of the accidents may prevent the further performance of tender activities indefinitely (Rowlinson, Yip and Poon, 2009).

According to the Summary of Occupational Safety and Health Statistics, the total numbers of accidental cases increased by 4.9% from 2016 to 2017. In 2017, there were 3902 cases of accidents recorded including 22 fatal accidents. Thanks to those initiatives, the industry experiences a decrease in the numbers of accidents by approximately 11.9% in the first quarter of 2018. There were 716 occupational accidents recorded including three fatalities (Labour Department, 2018).

Construction jobs are usually physically demanding even for the fit and younger worker (Gibb, Leaviss and Bust, 2013). As mentioned earlier, Hong Kong processes an increasingly ageing workforce that 25.83% of the workers are above 50 years of age. Compared to a younger worker, workers 50 years and overexpose themselves to a higher risk of injury (Maertens *et al.*, 2012). Older workers are more likely to suffer muscle fatigue, musculoskeletal disorders (MSDs), pneumoconiosis, and bone fractures than the younger workers (Kines, Spangenberg and Dyreborg, 2007). This is due to the declining of physical condition by ageing, which is a natural process. However, in this ageing worker dominated industry, this will lead to many health and safety-related issues (Nygård, Luopajarvi, & Ilmarinen, 1991). The Hong Kong construction industry should provide an environment that is suitable for the older workers, otherwise, the ageing workforce will have negative health and safety contribution towards the industry (Rowlinson, Yip and Poon, 2009).

There are various legislations in place to regulate an employer's action and duty to ensure on-site safety, also to provide legal protection for worker's welfare once accidents occur. The Employees' Compensation Ordinance Chapter 282 Section 7, which was enacted in 1953 (Poon, Tang and Wong, 2008) explains the amounts of compensation related to the seriousness of the occupational injury, incapacity level, or death caused by work according to the age of the employees, see Table 6, Table 7.

Table 6: Compensation for permanent total or partial incapacity, according to (Labour Department, 2019).

Compensation for permanent total or partial incapacity	
Age at time of the accident	**No. of the month of compensation**
Under 40	96
40 - 55	72
56 or above	48
e.g. HK$ 21,500 X 96 months = HK$ 2,064,000	

Table 7: Compensation is payable for an accident causing death, according to (Labour Department, 2019).

Compensation is payable for an accident causing death	
Age at time of the accident	**No. of the month of compensation**
Under 40	84
40 - 55	60
56 or above	36
e.g. HK$ 21,500 X 84 months = HK$ 1,806,000	

The claimable monthly compensation is subject to a maximum HK$ 21,500 for expected compensation. There are various channels that claims can be settled between the employer and employees. For example, the payment can be settled by direct payment, through court procedures or through a "Certificate of Compensation Assessment" that is issued by the Commissioner for Labour. If the employee suffers a non-fatal injury, apart from the compensation payable for the loss of earning capacity caused by the injury. The employer is also liable to pay medical expenses, which includes medication, surgical or therapeutic treatment, and nursing. In the case of a fatal case, the employer is liable to cover funeral costs, medical fees as well as compensation for the members of the family. In addition, the employer must provide liability insurance to cover any foreseeable injuries of the employees (Labour Department, 2018).

2.2.6 Productivity drivers and hinders

Productivity is often the main parameter that is used to measure how advanced an industry performs. Hong Kong will experience an increased level of construction projects in the coming years while suffering unvarying productivity decline. The productivity decline is partly contributed by high construction cost, ageing labour force, and serious skill shortage (Javed *et al.*, 2018). The Committee on productivity has provided communication channel among the industry, government, and stakeholders. It aims to inspire construction technology innovation to enhance overall productivity (Wong, Zhang and Lee, 2015). There are multiple constraints and attributes that could influence construction productivity. For example, the factors that improve productivity include prefabrication method and technology adaptation (Eastman and Sacks, 2008). The factors that hinder construction productivity include rework, logistics delay, and defects of construction materials (Palaneeswaran *et al.*, 2008). According to the research conducted by The University of Hong Kong, the drivers and constraints on construction productivity enhancement include the following five strategic points.

1. Policy
   The government policy has huge implications on the improvement of the current construction industry. Policies on new technology adoption, labour training or incentive plans for the contractors can strengthen the industry competitiveness by improving productivity, and collaboration (Barbosa *et al.*, 2017), (Green, 2016). However, regulations and policies often take longer time periods to pass; this also depends on the nature of the regulations, policies, and the priority of the local authority.

2. Regulatory
   Imposing regulations have both positive and negative impact on construction productivity. The implementation of health and safety regulation, employment conduct, and planning regulation can contribute positive influence on productivity (Choudhry, 2017). However, a heavily regulated industry often experiences complex internal and external structures or code of conduct to assure compliance.

3. Planning and design
   The prefabrication industry has demonstrated many similarities to the manufacturing industry. The Industrialized housing is usually prefabricated and assembled on-site; extensive off-site fabrication provides a clean and safe working environment and a repetitive work task allows integration of automation and the usages of specialised tools. The various building tasks are incorporated into different stages of assembly, which provide minimum on-site erection, joining and finishing work. Prefabrication allows on-site material handling to be mechanized due to standard building components and means of connection (Pan, Gibb and Dainty, 2008). However, to set up an off-site prefabrication facility it will inevitably consume significant amounts of initial investments, which may cause a negative impact on productivity (Pan and Sidwell, 2011).

4. Project management
   Management system, economic environment, construction schedule planning, labour management, and project complexity may have a positive and negative impact on project progress and productivity. Good project management can result in a smooth workflow, efficient workforce, well-organised logistics and material flow. In contrast, inadequate planning could lead to project delay, over budget and potentially putting worker's safety in danger (Dai *et al.*, 2009).

5. Construction innovation
   Implementation of advanced technologies and building method will potentially improve productivities, reduce labour, time, and improve quality. However, R&D activities require a considerable amount of investment. The construction industry is slow in adopting new technologies compared to other industries. The investors and property developers do not see financial incentives to implement new technologies, especially when those technologies may change the traditional supply chain that they are familiar with (Lee *et al.*, 2008). In addition, the new technology will require extensive testing and pilot run before deployment. Therefore, tangible means of productivity gain is hard to estimate in advance.

2.3 Hong Kong public housing construction sector

The dissertation will focus on analysing the methods of how to successfully implement automation and robotic technologies in the PHC sector in Hong Kong. It is crucial to understand the current situation, demands, weakness and strength of the industry. The following section will provide an overview of the history, the existing construction methods implemented, and achievements from the Hong Kong PHC sector.

2.3.1 Characteristics of the Hong Kong public housing

The history of public housing in Hong Kong can trackback 50 years. According to the HKHA, 50% of the population live in a public housing unit today. Originally, like other government, Hong Kong authority was not involved in supplying housing. This was transformed after several waves of immigrants. Between 1945 and 1951 the population grew from 600,000 to nearly 2.3million, in which more than 300,000 people lived in squatter conditions. The first involvement of the government in supplying housing to the public sector was after the Shek Kip Mei fire in 1953 that made 53,000 people homeless. The government, along with the former Housing Authority, took action in supplying low-cost dwellings that accommodate the fire victims as well as the rehouse the huge numbers of urban squatters. Despite the government's efforts and the resettlement programme in the early 1960s, there are still more than 600,000 people living under squatter conditions (Lee and Ngai-ming, 2006). In 1964 "Review of Policies for Squatter Control, Resettlement and Government Low-cost Housing" was published as a guideline to improve living environments of the poor (Smart, 2002). During this period many public housing types were developed; the detailed description will be illustrated in the following section. In the late 1960s social unrest broke out and one of the causes was due to overcrowded living condition amongst the working classes and the underprivileged population. As part of the Ten-year Housing Programme. The new HKHA was established, and more affordable adequate dwellings were planned to accommodate more than 1.8 million population between the year 1973 and 1982. Today the HA and Hong Kong Housing Society (HKHS) are still tackling the public housing issues by supplying PRH and subsidized homeownership housing. Currently, the main objectives of the HKHA include to provide affordable rental housing to the low-income families and to provide subsidized homeownership housing for low to middle-income families (Hui, 2001). From 2016 to 2017, there were 14,300 units of public housing constructed. According to the latest government projection, the housing supply target for the next decade is approximately 460,000 units, which including 200,000 PRH units and 80,000 subsidized sale flats. This is a huge challenge faced by the HKHA, as well as PHC, if there are no radical changes in the construction industry, to meet those targets will seem to be over-ambitious, nevertheless, one of the reasons why the project has chosen Hong Kong and Hong Kong PHC as a case study (Hong Kong Housing Authority, 2018).

2.3.2 The existing Hong Kong public housing construction strategies

The first public housing estate was constructed in 1954 where the Shek Kip Mei fire erupted. As part of the resettlement programme, Mark I to Mark VI type flats were developed between 1954 and 1970. Mark I blocks were designed to be back-to-back, with communal kitchen and bathroom. Usually, the blocks are six or seven storeys high and designed in an "H" shape. The living space was rather congested for today's standard. Only 11.15 m^2 of inhabitable space for five adults. Mark II blocks first appeared in Tung Tau Tsuen in 1961, and the design is very similar to Mark I, but it offers larger accommodation and private kitchen and washroom. The

Mark III Blocks were constructed around 1964 in Kwai Chung Estate. The blocks are eight storeys high with a very similar design as the Mark I, and Mark II, the only obvious difference is that each flat was given a private balcony and with shared access through a central corridor. Mark IV blocks were constructed between 1964 and 1969. The blocks are commonly 19 storeys, equipped with lifts, and this was also the first time private lavatories were equipped in public housing. Between 1966 and 1971 the Mark V and Mark VI blocks were launched, there were not many changes from the predecessor. In comparison, Mark V and Mark VI blocks had bigger living accommodation than Mark I to Mark V blocks. Even though the buildings were only provided rudimentary housing for the designated population, they still have a significant impact on the development of public housing in Hong Kong, in which shared valuable history. After the 1970s, new types of public housing blocks were developed, including Twin Tower, Slab, Cruciform, Single H Type, Double H Block, Trident, Harmony, Linear, Concord, New Cruciform Block, and Non-standard (Hong Kong Housing Authority, 2019), (Choi, 1998), see Figure 3.

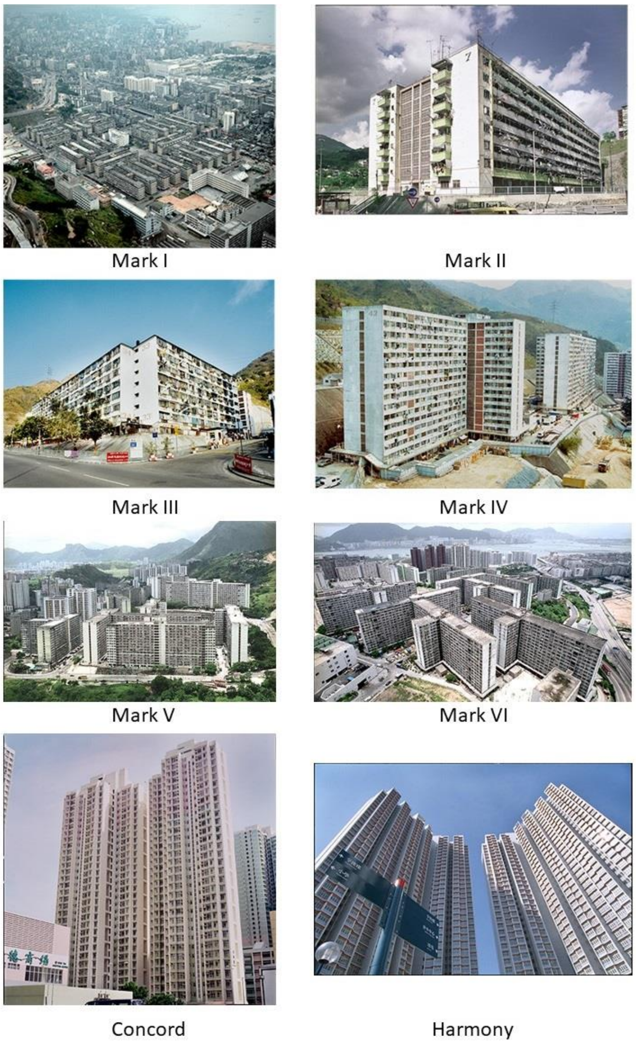


Figure 3: The history of Hong Kong public housing design, source: (Hong Kong Housing Authority, image courtesy of Mr. KH Chu).

Since the 1990s, Harmony and Concord block series remain the most popular types of public housing for the HA. The popularity is due to the regular shape of the building and repetitive configuration so that the building components can be prefabricated off-site. Prefabrication is to be considered as the first step towards construction industrialisation, then automation and robotics is the ultimate ambition of construction industrialisation (Richard, 2005). Even though off-site prefabrication and the modular building were mentioned in the early section, they are not the main scope of the research project. However, it is still imperative to gain an understanding of how prefabrication has influenced Hong Kong PHC sector, in terms of construction methods, standardization, customization, and management. The achievements in prefabrication will facilitate the use of automation and robotics both in the off-site facilities and on-site operations.

In general, prefabrication can be described as a manufacturing process, generally conducted at a specialized facility either in an off-site factory or on-site prefabrication, in which various materials are joined to form a component part of the final installation (Jaillon and Poon, 2009). Adopting prefabrication can effectively decrease the number of workers on-site and potentially increase the efficiency of the overall project. Off-site prefabrication can be categorised as the non-volumetric, volumetric and modular building that involves high degrees of standardization, customization, effective technology integration, adaptable organizational, and managerial implementation (Gibb, 1999).

Prefabrication technologies have been developed and adopted in Hong Kong PHC sector since the 1980s that enable a better understanding of the potential of adopting prefabricated building, components, and parts for the stakeholders in the Hong Kong construction industry. The CIC commissioned Mercado Solutions Associates Limited to conduct the industry investigation. The investigation was conducted through a questionnaire, telephone and face-to-face interviews between July and September in 2016. In total, there were 648 questionnaires from different stakeholders collected including 21 from Owners' organizations such as governmental departments, public utilities and private developers, 121 from consultants and 506 from Builders. This summary provides the main findings of this survey. Of the results indicated out of all respondents, approximately 24.5% used prefabricated components in construction projects two years prior to the investigation. The data collected from the expert interviews showed that the public sector tends to widely and frequently use prefabrication components. The main reason is that public works have a standard design and building styles, and the application of prefabricated components is well developed (Construction Industry Council, 2017). The most popular precast components include staircases, external wall, partition walls, floor slabs, and balconies. Precast volumetric components consist of a kitchen pod module and bathroom pod module. After decades of experience and determination, Hong Kong PHC sector has pioneered adopting prefabrication technologies extensively.

In public housing projects, buildings are generally designed with regular shapes, see Figure 4. A regularly shaped building will ease the use of standardised components such as wall panels, floor slabs, and increase repetitions, and therefore increase the speed of construction. In most of the public housing projects, a six-day construction cycle was adopted, which means it is mandatory to complete each floor within six days (Chan, D.W., & Chan, A.P., 2002).

Construction of Public Rental Housing Development at ex-Kwai Chung Police Married Quarters building was selected as a case study to analyse the rapid construction sequence. The typical six-day working cycle in Harmony block is as follows, see Table 8.

Table 8: Typical six-day working cycle in Harmony block, according to (Hip Hing Construction Co., Ltd).

	WING A	WING B	WING C	WING D
Day 1	07:00-08:00 Wall-ties for concrete forms	07:00-08:00 Wall-ties for concrete forms	07:00-10:15 Disassemble steel form work support	07:00-10:15 Disassemble steel formwork support
	08:00-11:00 Wall reinforcement Fixing	09:30-11:00 Install precast wall façade & supports for prefabricated toilet pod	15:00-17:00 Disassemble steel formworks	11:00-14:00 disassemble steel formworks
	08:00-9:30 Install precast wall façade & supports for prefabricated toilet pod	11:00-16:00 Wall reinforcement Fixing	17:15-19:00 Install the truss works internally	11:15-16:00 Install the truss works internally
	10:00-11:00 Inspection for Clerk of Works, Building service inspector (COW/BSI), walls	15:00-16:00 Inspection for COW/BSI, walls		17:00-19:00 Erection of the steel formwork & install the precast floor panel
	10:00-18:00 Install prefabricated toilet pod	10:00-18:00 Install prefabricated toilet pod		
	11:00-15:00 Install steel formworks	15:00-17:00 Install steel formworks		
Day 2	07:00-12:00 Adjusting the steel formwork	07:00-12:00 Install and adjust steel formworks	07:00-12:00 Steel formworks, truss, and installation of the precast staircase	08:00-09:00 Floor reinforcement positioning
	08:00-18:00 Grouting of the prefabricated toilet pod	08:00-18:00 Grouting of the prefabricated toilet pod	13:30-15:00 Rises of the steel formwork & install the precast floor panel	09:00-19:00 Floor reinforcement fixing
	08:30-09:00 Reinforcement positioning for door and walls	13:00-13:30 Reinforcement positioning for door and walls	15:00-16:00 Floor reinforcement positioning	13:00-19:00 Electrical installation
	09:00-14:00 Reinforcement fixing for door & wall sections	13:30-16:00 Reinforcement fixing for door & wall sections	16:00-19:00 Floor reinforcement fixing	
	14:00-15:30 Inspection for COW/BSI, walls	16:00-17:00 Inspection for COW/BSI, walls	17:00-19:00 Electrical installation	
Day 3	08:00-12:00 Concreting of the shear wall	13:00-15:00 Concreting of the shear wall	07:00-15:00 Floor reinforcement fixing and electrical installation	07:30-12:00 Floor reinforcement fixing and electrical installation
	08:00-18:00 Disassemble the temporary supports	08:00-18:00 Disassemble the temporary supports	14:30-15:00 Inspection for COW/BSI, walls	10:30-12:00 Inspection for COW/BSI, walls
			17:00-19:00 Concreting floor, and screeding	15:00-17:00 Concreting floor, and screeding

Day 4	07:00-10:15 Disassemble steel formwork support	07:00-10:15 Disassemble steel formwork support	07:00-08:00 Wall-ties for concrete forms	07:00-08:00 Wall-ties for concrete forms
	11:00-14:00 Disassemble steel formworks	15:00-17:00 Disassemble steel formworks	09:30-11:00 Install precast wall façade & supports for prefabricated toilet pod	08:00-11:00 Wall reinforcement fixing
	11:15-16:00 Install the truss works internally	17:15-19:00 Install the truss works internally	11:00-16:00 Wall reinforcement Fixing	08:00-09:30 Install precast wall façade & supports for prefabricated toilet pod
	17:15-19:00 Rises of the steel formwork & install the precast floor panel		15:00-16:00 Inspection for COW/BSI, walls	10:00-11:00 Inspection for COW/BSI, walls
			10:00-18:00 Install prefabricated toilet pod	10:00-18:00 Install prefabricated toilet pod
			15:00-17:00 Install steel formworks	11:00-15:00 Install steel formworks
Day 5	08:00-09:00 Floor reinforcement positioning	07:00-12:00 Steel formworks, truss, and installation of the precast staircase	07:00-12:00 Install and adjust steel formworks	07:00-12:00 Adjust steel formworks
	09:00-19:00 Floor reinforcement fixing	13:30-15:00 Rises of the steel formwork & install the precast floor panel	08:00-18:00 Grouting of the prefabricated toilet pod	08:00-18:00 Grouting of the prefabricated toilet pod
	13:00-19:00 Electrical installation	15:00-16:00 Floor reinforcement positioning	13:00-13:30 Reinforcement positioning for door and walls	08:30-09:00 Reinforcement positioning for door and walls
		16:00-19:00 Floor reinforcement fixing	13:30-16:00 Reinforcement fixing for door & wall sections	09:00-14:00 Reinforcement fixing for door & wall sections
		17:00-19:00 Electrical installation	16:00-17:00 Inspection for COW/BSI, walls	14:00-15:30 Inspection for COW/BSI, walls
Day 6	07:30-12:00 Floor reinforcement fixing and electrical installation	07:30-15:00 Floor reinforcement fixing and electrical installation	13:00-15:00 Concreting of the shear wall	08:00-12:00 Concreting of the shear wall
	10:30-12:00 Inspection for COW/BSI, walls	14:30-15:00 Inspection for COW/BSI, walls	08:00-18:00 Disassemble the temporary supports	08:00-18:00 Disassemble the temporary supports
	15:00-17:00 Concreting floor, and screeding	17:00-19:00 Concreting floor, and screeding		

As illustrated in the table above, the construction speed for the case study building was astonishing. Because of, first, the building with symmetric axes or wings allowing repetition and reuse of the lost form (or Slip form system), second, standard design and prefabricated components, and last but not least, diligent management paired with team efforts.

Recently, MiC started to gain popularity in Hong Kong. MiC can be classified as a type of industrialized volumetric modular building system, wherein parts and components are assembled in an off-site facility to form a freestanding integrated module completed with interior finishes, services fittings, necessary appliances, and later on assembled on-site.

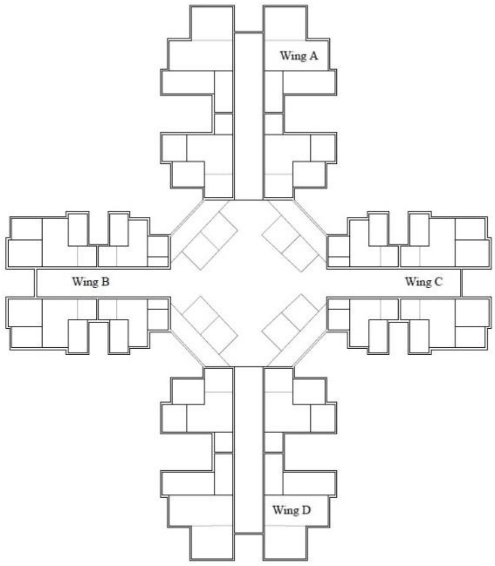


Figure 4: The typical floor layout of the Harmony block.

Some early examples of MiC can be found in 1960's Japan and post-war period Germany, and in which addressed some critical issues similar to what Hong Kong faces today. The Nakagin capsule tower was constructed in 1968 in Ginza, Japan, designed by Kisho Kurokawa, which represented the Metabolism Manifesto or "New Urbanism" movement. The building reflects the concept of a future city with architecture capable of growing and changing by the demand. The principle behind the manifesto was that rather than being fixed machines, architecture and cities should be organic, growing through metabolic processes of change and renewal (Girardet, 1990). The second example is Metastadt that was constructed in 1965, in Wulfen, Germany, designed by Richard J. Dietrich and Bernd Steigerwald. The building demonstrated the typical feature of MiC: the space frame structure itself is bolted to allow easy assembly and disassembly; everything remains changeable and adaptable. The infill system is separate from the structural system; the living spaces and offices have demountable walls whilst partition walls in apartments are made of plasterboard. Both examples illustrate the advantages of Mic, which include Design for manufacturing and assembly (DfMA), which eases production and speeds up the on-site installation process. Second, the design decision is well defined prior to manufacturing, which reduces alterations and design changes to occur in the later stage. In addition, it is material saving, higher quality, safer, environmentally friendly and increases overall productivity. Hong Kong local authority and the CIC values MiC highly, and huge efforts were made to promote the concept. The CIC has commissioned the MiC Display Centre in November 2018 to showcase the design, function and requirements of the MiC flats to the public, see Figure 5. From the governmental level, the Building Department, Electrical and Mechanical Services Department, and Water Supplies Department offered guidelines, advice, and numbers of pilot projects that were initiated to facilitate the implementation of MiC in Hong Kong (Construction Industry Council, 2019).

BIM is being increasingly implemented in the construction industry to assist with data collection and processing (J. Wong et al., 2015). Hong Kong construction industry also adopted

BIM to improve the overall performance of the projects as well as productivity. In the years 2008, 2009, and 2010 the HKHS included BIM into to its programme of activities for housing development, and several schemes were launched include using BIM to improve the design, operational efficiency, and planning. In addition, the decision was made to use BIM in the public housing project in 2009. Since then, with the help of in-house BIM standard and design libraries, more than 19 public building projects have adopted BIM in different stages of the project (A. K. D. Wong, Wong, & Nadeem, 2011). As mentioned earlier, there are other types of innovative technologies implemented in the Hong Kong Construction sector, such as Radio-Frequency Identification (RFID), advanced machinery, and automation and robotics, but not yet being applied in the PRH sector.

Figure 5: The MiC Display Centre, source: (QianRu Du).

2.4 Constraints and advantages of the Hong Kong construction industry

This section provides an overview of the challenges faced by the Hong Kong construction industry, some of which evidently represent the uniqueness of Hong Kong. Aside from the challenges, the advantages of Hong Kong’s economy, geographic location, innovation achievements, and research capabilities have also been examined.

2.4.1 Constrains

Hong Kong has one of the least affordable private property markets in the world, with 20.9 times the gross annual median income (Demographia, 2018). That means if an individual with an annual income of HK$ 500,000 a year, he has to set aside approximately HK$10,450,000 to be able to afford a property. Most of the people consider property as a means of an asset to protect them from an insecure future. A new trend of choice called Micro flat has emerged, which focuses on young professionals, who would like to gain an upper hand in entering the property ladder. The average size of the Micro flat is approximately 21m^2 and can cost up to HK$3,900,000 according to interviews with the prospective buyer. For many people, it is unaffordable to purchase private-sector homes and it still increasingly depends on the PRH or subsidized Homeownership Scheme (HOS). There is a hidden social pressure and cost in China due to the expectations placed on young adults to own private homes in order to start a family. Especially for an adult male, establishing his social status and proving to his in-laws that he has the means to look after the spouse is very important. For many, unable to afford such commodities, the possible outcomes are that if parents own private property, adult children can rely on their parents to make the initial down payment, and parents can refinance their existing home for that purpose. If they lived in a PHR, then the parents leave and the children stay, or the opposite, and the party who is leaving needs to either secure another PHR or seek for an arrangement with the HA or relatives (Wong, 2015). However, the average waiting time for PHR is 5.5 years, and the average waiting time for elderly one-person applicants is 2.9 years in 2018 (Hong Kong Housing Authority, 2018). Researchers have linked falling fertility rates with this social phenomenon. Falling fertility rates can cause direct or indirect implications in the construction sector. For instance, falling fertility can contribute to faster demographic changes, while labour shortage could affect productivity, wages, and potentially increase the overall construction costs. In reverse, a higher construction costs could eventually push up property costs even higher (Yi and Zhang, 2010). Evidently, the security and ownership of property are critical to social and economic empowerment and many issues are intertwined with the construction sector. Hong Kong needs a long-term strategy that expands homeownership, particularly increasing the numbers of affordable housing. On the other hand, as mentioned earlier, Hong Kong faces high construction costs, land shortage, labour and skill shortage, and productivity decline; hence, solving the increasing demand of PRH has imposed a very challenging task for the PHC sector.

Over the years, the HKHA has promoted prefabrication and standard industrialized building systems in order to improve the overall productivity of the PHC sector. This allows larger contractors, who adopt such technologies to capitalise on their financial means, technological competence, and managerial experiences. However, it also potentially creates an entry barrier for smaller domestic contractors, many of which still heavily rely on traditional methods and labour force, and lack of finance to improve their technical input. Most of the local contractors are Small and Medium-sized Enterprises (SMEs), and without adequate government supports it will be very difficult to compete with overseas or mainland China contractors, which often have strong government back-ups, and possess greater resources. Without adequate government support, Hong Kong PHC sector as a whole will find them in an intricate situation, especially when competing in the increasingly competitive global construction market. Therefore, increasing productivity by adopting innovative construction technologies can potentially increase the competitive edge of Hong Kong PHC sector (Lee *et al.*, 2008). On the other hand, lack of long-term strategy, financial support and incentive will result in slow acceptance of new technologies. From the government's perspective, lack of mega-sized projects can reduce the incentives or motivation to invest in R&D. From the contractor's perspective, without systematic planning, support and leadership from the government, so for them, it is not mandatory to implement innovative technologies. However, as the author has found, in addition to mega infrastructure projects, the PHC projects also involve urgent government and construction professionals to help solve the above-mentioned problems. The challenges also impose huge opportunities for researchers, government authorities, and industry experts to work alongside with each other, seeking solutions to satisfy the PHC market demand, improve productivity, and modernise the Hong Kong construction industry as a whole.

2.4.2 Advantages

Other than the constraints, Hong Kong also indicates several advantages in terms of economic and technological advances, and sheer determination in changing the construction industry into a more innovative, competitive, and sustainable one. In 2018, the Hong Kong economy and GDP grew by 3%, while unemployment rates decreased by 2.8% (China Daily, 2019). This indicates, despite the U.S. – China trade tensions, Hong Kong remains one of the faster-growing economy as well as benefit from its economic freedom (Chiu, Ho and Lui, 2018). Hong Kong has an internationally renowned higher education reputation including 21 degree-awarding higher education institutions. Education excellence has a positive implication on Hong Kong's R&D competence (Cheng, Jackson and Lee, 2017).

The Hong Kong construction industry has gained a positive reputation for its rapid speed, high quality, flexible approach and expertise in extreme construction projects such as super high-rise building construction, slope design, high-density solution, and vertical urban planning. Thanks to the large- scale projects over the years, Hong Kong has possessed some of the most experienced engineers and construction project management experts. Hong Kong professionals have been active in project design and management tasks throughout mainland China and other developing nations that allow them to capitalise on broad experience and keep market competitiveness.

In regards to construction innovation, there are some outstanding academic breakthroughs, which facilitate construction technology upgrading. The Hong Kong University of Science and Technology (HKUST) has launched the HKUST robotic institute and developed Robotics and Autonomous Systems (RAS) that operate with a high degree of autonomy, which can be used for site survey, infrastructure maintenance, and later can be used on other construction applications. In the aspect of the construction industry, besides implementation of prefabrication, BIM, and modular construction technologies, there is a growing trend that the industry is exploring automation and robotics in hopes that adoption of automation and robotic technologies will hold the key to transfer the industry from labour-intensive to a high-tech industry. Currently, there is little practical robotic application use in the industry, yet one of the Hong Kong metal fabrication companies named program has adopted industrial robotic arms in the off-site production line. The robot is designed to weld construction metal elements.

The CIC is also taking the lead to establish research initiatives that aim to set up long-term strategies in solving construction-related issues and improve the performance of the construction industry in Hong Kong. The CIC has invested HK$10M yearly to fund research projects to stimulate technological innovation in the industry (Wong, Zhang and Lee, 2015). As part of the CIC, CITAC regularly showcases the carefully selected state of art construction technologies that demonstrate practicality, ingenuity, and inspiration to the Hong Kong construction industry. CITAC also provides a platform that facilitates collaboration, technological exploitation, and networking. Since 2015, the CIC innovation award has taken place yearly to encourage continuous innovation aspiration in enhancing the construction industry.

The Hong Kong Science and Technology Parks Corporation (HKSTP), is a public corporation set up by the HKSAR government in 2001. The launch of HKSTP indicates that the government is dedicated to promote Hong Kong not merely as a financial hub of Asia, but the leader in innovation and technological development. Now, HKSTP is the largest R&D centre in Hong Kong, a leading incubator for start-up companies, and a transparent communication platform. The initiatives and funded research focus on three topics: Smart City, Healthy Ageing, and Robotics. In December 2017, the Robotics Catalysing Centre (RCC) was launched, which facilitates robotic R&D, assembly, validation, and assists the companies with factory acceptance test (FAT) prior to market launch. Currently, out of the total numbers of 680 companies in HKSTP, one company called O-MATIC Intelligent Robot Limited is known to focus on construction robotics (HKSTP, 2019).

Last but not least, the strategic location of Hong Kong, comprehensive taxes, trade, legal advantages and close proximity to one of the world's largest economies must bring outstanding advantages to its development. After the completion of the world’s longest sea-crossing bridge, that links Hong Kong with Macau, Zhuhai. The Chinese government has announced to form a new economic region, which links Hong Kong with Macau, Guangzhou, and Shenzhen to create a so-called Dawan (Great bay) district. The plan states the four cities would be the core engines for the regional development. Notably, Hong Kong will be the centre of finance, trade, logistics, professional services, and innovation. Key initiatives include talent exchange, entrepreneurship incubation, research facilities and funds, venture finance, the transformation of results, and in-depth cooperation. With the collaboration between education institutes, the industry and government, R&D initiatives, the combined efforts will inject momentum into the development of Hong Kong's innovative economy and jointly enhance Hong Kong's overall competitiveness. With the complementary advantages of Dawan District, coupled with the development of the future Hetao District, Hong Kong will be able to seize the opportunity and continue to develop its strengths. To build up a platform for cooperation between Guangdong, Hong Kong and Macao aims to become a key research base in Dawan District, enhance technological innovation, the transformation of results and market applications, and, with close collaboration, to build Dawan District into an international science and technology innovation centre (KPMG Huazhen LLP, 2019).

2.4.3 Summary

The Hong Kong construction industry faces many challenges as well as embraces many advantages. However, the local construction industry already achieved high speed, quality, and an abundance of experiences. On the other hand, as a whole, the construction industry is still relatively conventional when compared to the other sectors. The PHC industry still faces a rapid increase in housing demand and a lack of development land and skilled labour force. Therefore, the construction productivity needs to be continuously improved in order to meet the HKHA’s target of providing 460,000 units in the next decade (Hong Kong Housing Authority, 2018).

Hong Kong has the upper hand in gradually transforming the PHC industry to a high-tech driven industry. As mentioned in the previous section, there is evidence that CIC, HKSTP, and academia attempt to explore the potential of automation and robotics in construction. Consequently, CIC has approached Professor Thomas Bock at TUM to discuss how to implement OCR in the case of Hong Kong PHC industry. In the current PHC industry, the systematic and scientific method to approach this type of study, especially when closely associated with the industry and authorities, has not been comprehensively discussed. Automation and robotic technologies can offer an alternative solution to some of the aforementioned challenges, but it cannot be appraised as a universal proposition for all construction-related issues. The next section will focus on analysing the history and potential of OCR technology and the potential implications on the construction industry (Pan, Wen *et al.*, 2018).

2.5 Construction automation and robotic

This section provides an overview of the general concept of the industrial robot. Here the question arises about why an industry would need to adopt automation. In principle, an industrial robot is designed based on the specific industrial task under special circumstances, and with the explicit objective to achieve specified KPIs. The OCR will be developed for the construction industry so that it can be referred to as a different typology of the industrial robot. Hence, it is important to be familiar with the parts, components, and the standard approach when developing an industrial robot. Yet, there are some fundamental differences between the manufacturing industry and the construction industry. So that when designing OCR, many aspects related to construction, on-site condition, availability of technology, and competences of the skilled labour must be considered. In order to understand what has been done in regards to construction automation and robotics, the author demonstrated the existing examples as well as the state of art applications that have been successfully commercialized.

2.5.1 Industrial robot

The development and introduction of the automation system and robotic technologies have successfully improved productivity, quality, operational safety, and economy aspect of many industrial sectors. Before embracing robotic technology in the construction industry, it is vital to be conscious of the development history, purpose and function of industrial robots, which in some respects are extremely similar, yet essentially distinct from OCR.

The general public often portrays an industrial robot to be a humanoid robot, which can be as flexible and sensible as a human worker. In fact, an industrial robot can be described as a programmable manipulator, which is capable of moving on two or more axes. The industrial robot is equipped with specific tools called end effectors that enable the robot to perform predefined tasks, and the control programs influence the robot's action. The industrial robot can be reprogrammed to perform a different motion or task without changing hardware (Ardayfio, 1987). The advantages of an industrial robot include great precision when performing highly repetitive tasks, indefatigable availability, and resilience of the harsh operational environment. The human worker still outperforms the industrial robot in the following aspects. First, the capability of proactive response to unforeseen circumstances and changing environments. Second, the ability to work as a team. Third, the ability to use inductive reasoning, and to exercise judgment (Fitts, 1951). Finally, the ability to improve performance based on previous experiences. With the development of Artificial intelligence (AI) technology, Machine learning (ML), sensor technology, the future industrial robot will able to perform in a wider range of environment, under more complicated conditions and require less human or program instructions (Ayres, 1981).

George Devol invented the first industrial robot back in 1954. The robot is designed to be a programmable material transfer device. Later, George Devol founded the first robot company, Unimation, with his business partner Joseph Engelberger. The robot was put in to test at a General Motor plant in 1961, and it was performing material extraction from a die-casting machine. During the same time, Unimates developed large material handling and spot-welding robots. Those early applications operated successfully and proved the robot is reliable and provides constant quality. Ever since many companies were dedicated to industrial robot development, for instance, Victor Scheinman developed the Stanford Arm prototype in 1969, which possesses 6-DOF and all-electric manipulator controlled by a conventional computer. The robot was the first of the kind equipped with a direct-current (DC) electric motors, harmonic drive, spur gear reducer, potentiometers, and tachometers for position and velocity feedback. Consequently, the design has influenced later robotic designs (Hägele *et al.*, 2016).

In general, the choice of mechanism, kinematic properties of an industrial robot depends on the specific task, payload, work envelope, and the motions required while executing the task. The commonly employed kinematics for industrial application include Gantry (Cartesian), SCARA, Articulated, Cylindrical, Polar, and Delta. Each one of them has a specific movement range and work envelope; these factors often determine the optimum combination between tasks and deployment of the appropriate robot, see Figure 6.

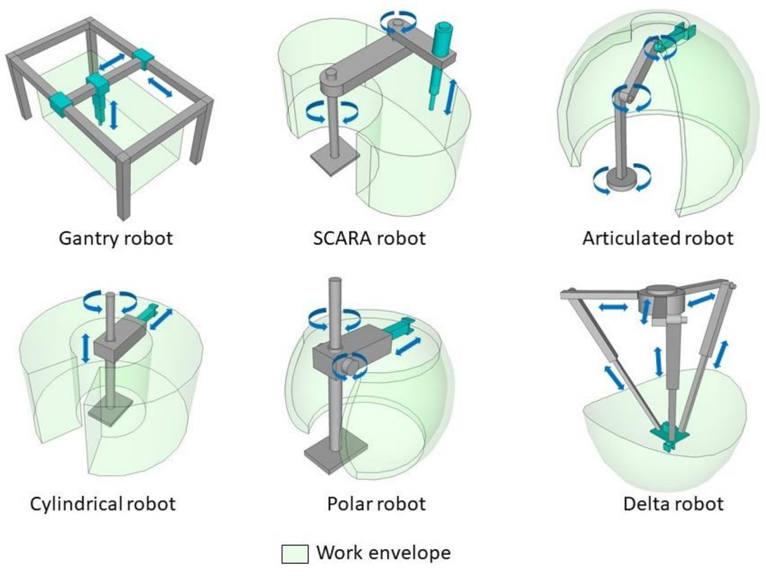


Figure 6: The commonly employed kinematics for industrial robots.

The industrial robot serves human in three ways: as a tool enhancing a specific task, a tool that augments human performance, and a tool to replace humans completely. The level of autonomy discrepancies and allocation of tasks between human and robot hugely depends on the nature of the specific industrial practice. In many aspects, humans and robots are not interchangeable, but complementary (Jordan, 1963). Most tasks that an industrial robot is allocated to carry out are those that require high repetition, high precision, large payload, and that are hazardous for human workers. The typical industrial applications include welding, automobile assembly, painting, material handling, and machining. The kinematic properties of the main type of industrial robot and the suitable applications are described below, see Table 9.

Table 9: The kinematic description and application of the main type of industrial robot.

Type	Description	Application
Gantry robot	Travel within X-Y-Z coordinate plane, and with linear movement	Pick and place task, sample assembly task, arc welding application
SCARA robot	Travel within X-Y-Z axis, with an additional theta axis at the end of Z plane to rotate the end effector	Pick and place, compliance assembly, tool handling
Articulated robot	Employs up to six-axis with a rotary joint on each arm	Assembly, die casting, gas, arc welding, material handling, painting, machining
Cylindrical robot	Rotary joint travel on a linear joint to offer a cylindrical work envelope	Assembly, spot welding, tool handling
Polar robot	Two rotary joints combined with a linear joint to offer a spherical work envelope	Spot, gas, arc welding, die casting
Delta robot	Joints connected based on a parallelogram to offer a half dome-shaped work envelope	Assembly, pick and place, material handling, machining

In order to perform the assigned tasks, the industrial robot often acquires the following configuration and feature. Since most of the industrial applications require the robot to remain stationary, a base frame is often equipped along with power supply sources, actuators, sensors, end effectors, and control software. The power source for an industrial robot is usually an external power supply, where sometimes an inverter is required if the robot uses Alternating Current (AC) motor. In terms of mobile robot applications such as Automated Guided Vehicle (AGV), or Unmanned aerial vehicle (UAV) or drone, batteries are the most common choice as the source of power. Depending on the robot type and task requirements, the common type of batteries includes nickel-cadmium (NiCd), lead-acid, and lithium-ion batteries.

The industrial robot relies on a motor or actuator to provide movement, and to gain appropriate payload. Therefore, the selection of the optimum specification of the motor is very important to the robotic engineer. The engineer needs to take various factors into consideration when it comes to motor selection, such as mobility drive style, torque, velocity, precision, voltage, work envelope, task process, and cost. The most common types of motors include Stepper motor, Servo motor, Hydraulic, and Pneumatic motor. Stepper motors offer high torque, high precision, and relatively economical price. It is often used for the pick-and-place application. The use of servo motors has become more popular in almost every industrial applications due to servo motor offering reliable high torque performance, a high degree of precision, and control flexibility. Hydraulic and Pneumatic motors were commonly applied to early robots. For instance, a pneumatic motor is used to drive higher payload end effectors for heavy lifting applications. However, they offer greater payload and reduction ratio but impose some issues. For example, a hydraulic motor tends to be large in size, heavy in weight, slower, and spill hydraulic fluid under high pressure.

The main purpose of sensing technology is to assist industrial robots to understand the operational environment in real-time. Depending on the task requirements and operational location, the robot needs to be able to gather information through sensors, then to process them and finally make decisions based on the feedback from information processing. There are a variety of sensor types that were developed over the years, and the brief introduction of the most commonly deployed sensors are listed as below see Table 10.

Table 10: The description of the most commonly deployed sensors.

Sensor type	**Description**	**Application**
Touch	Touch or tactile sensors enable a robot to manipulate an object with the desired force	To detect the presence, fining centre position, guiding, polishing, insertion, material handling
Force	Force sensors enable the mechanical force to be converted into the electrical output signal, FS is normally equipped between the end effector and the robot	Assembly, guiding, teaching, welding
Proximity	Proximity sensor offers non-contact detection of presence or absence of objects by using, electromagnetic fields, high-frequency oscillation, light or sound	Assembly, objects detection, positioning, measuring, material handling
Position	An encoder either absolute or displacement position sensor that support position measurement	Safety, objects detection
Vision	2D or 3D vision used to detect, differentiate object, and coordinate position	“Bin picking”, material handling, inspection, objects detection, positioning, measuring
Safety	Laser sensor used to detect the presence or absence of objects	Safety, robot guarding, personnel protection
Part detection	Part detection sensor is used to detect the presence of the physical object	Assembly, material handling, parts finding, allocation and detection

The industrial robot needs a customised tool to perform assigned tasks. An end effector is the dedicated tool kit that is normally fixed at the end of a robot arm. It is acting as the last link of the robot (Hägele *et al.*, 2016). Some of the end effectors are modified from the conventional machine tools. However, some are advanced, have sensors and obtain more than one DOF. In industrial robotics, an end effector usually refers to a gripper or a tool that is specially designed to conduct the specific task. There are four major types of the end effector: Impactive, Ingressive, Astrictive, and Contigutive. The Impactive type refers to the gripper that has direct contact or impact with the object. The Ingressive type defines those end effector that use direct force to penetrate the object’s surface. The Astrictive type often applies suction forces to create contact with an object. Last but not least, the Contigutive type uses adhesive media to create direct contact with an object (DISTRELEC, 2019).

Adequate power supply, actuation, sensor technology, and end effectors are the fundamental factors to ensure a successful robot deployment. However, without a control system or sufficient processing power, a robot will only stay still. The common purpose controller deployed by most of the industrial robot application is the programmable logic controller (PLC), and the most applied control techniques include Open Loop control, Closed Loop control, Feedback control, Feedforward control, and Adaptive control (Groover, M and Nagel, 1986). Based on the selection of motor, task requirement also has major implications on the complexity of the control method. A program is required to instruct robots to process input data from the operator and sensor in real-time. As the task complexity increases, the more complicated it is to program a robot. Currently, there are many robotic programming languages in use, such as Controller-specific languages, Generic procedural languages, Behaviour-based languages, Graphical programming system, and Automatic programming system. In addition, there is a growing trend to use high-level programing language like Python, Visual Basic, and Ruby along with the advanced middleware, such as Robot Operating System (ROS) to ease the workload of the programmer, and to seek a universal solution that allows people without deep knowledge about programming to program the robot easily (Biggs and Macdonald, 2003).

The conventional industrial robot often operates separately from human workers. A cage or safety fence is usually erected as a safety measure. In the past decade, human-robot collaboration (HRC) has increased diametrically in many automated industrial applications. Many industrial robot systems still impose danger to the human worker due to their inertia, structure and operating force (Zinn, Khatib and Roth, 2004). Consequently, many safety standards were introduced. In particular, the ISO 10218- standard explicitly stressed the importance of operational safety measure in regards to HRC (Bauer, Wollherr and Buss, 2008). The safety measure for collaborative operation between human and robot can be summarised in four cases.

1. Safety-rated monitored stop: As long as the human worker is in the collaborative workspace (CWS), then the robot is not permitted to move. The robot can only be reengaged to working mode after the human worker left the CWS.
2. Hand guiding: The robot is directly controlled by a human worker. The motion, force and speed of the robot is directly influenced by inputs from the operator.
3. Speed and separation monitoring: The robot motion, force, and moving speed is determined by the use of real-time monitoring of the movement of the human worker.
4. Power and force limiting: The design consideration to prevent impact on the human body by robot transient force (Fryman and Matthias, 2012).

Developing optimal safety measures against static and dynamic force when collaborating with a robot requires a good understanding of the mechanical feature and the degree of human intervention (Haddadin, Albu-Schäffer and Hirzinger, 2010). As robots become more intelligent, better awareness of the CWS will be achieved, hence improving the safe operation of many industrial applications.

Having mentioned that above, a collaborative robot requires awareness of its surrounding, and the ability to optimise the performance from the past experience. This leads to the next topic of machine learning. The principle concept behind machine learning is to train the robot to learn the correct historical data and with the help of machine-learning algorithms, the robot will automatically detect and analyse new telemetry data as well as identify anomalies (O’Meara, Schlag and Wickler, 2018). The technology has been adopted in many applications, such as drones, and self-driving vehicles. Machine learning technology will embrace proactive sensory and control system development rather than the conventional rule or path based systems (DISTRELEC, 2019).

The used of robotics and automation in the manufacturing industry has become more and more mainstream lately. The infrastructure that supports robot operation has become more mature. As a result, robot expenses are becoming more affordable, related techniques have evolved quickly, business models have been created to fit the company's objectives, and the robotic services sector has given the required training and maintenance to accelerate the industry's growth. According to the statistics from the International Federation of Robotics (IFR), the global sales of industrial robots are expected to exceed 400,000 units in 2018 (Hägele *et al.*, 2016).

In this section, the author provides an overview of the principle and development of an industrial robot. Even though, there is a huge fundamental difference in OCR design and operation from the industrial robot. In terms of mechanism, kinematic properties, sensor technology, power supply, and control strategy, these two robot categories still share many similar characteristics. Therefore, understanding the basic knowledge of industrial robot can bare huge benefit when developing OCR systems.

2.5.2 Why and how to automate

The author would like to raise some of the often discussed and critical concerns when carrying out robotic system design. Why does the sector need to automate and how to decide what amount and type of automation are suitable for a particular job? In addition, the differences between industrial and construction operation will be analysed by investigating the difference in the nature of the tasks, working environment, and skills sets.

Automation and robotics have been treated as a suitable solution in solving industrywide challenges, such as increasing labour cost, declining productivity, labour shortage, safety, and improving quality. This is because robots are capable of doing many functions that once can only be performed by the human. In many aspects, robots can outperform human in terms of efficiency, endurance, precision and accuracy, and work quality. Yet in many cases, human performance appears to surpass robots, such as the ability to make the decision to solve unforeseen issues, ability to improvise and use flexible procedures, ability to reason and make adjustments, and ability to process a large amount of information and utilise them accordingly (Fitts, 1951).

The first question is why an industry decides whether or not to automate? The main motive could be surmised as financial benefit, safety, capability and preference (Scerbo and Ed Mouloua, 1999). Some manufacturing procedures are automated, for instance, because automation can possibly enhance productivity, increase production quantity and possibly decrease production costs. The human worker may be subjected to some natural barriers when it comes to working hours, pressure, temperature, and emotional effects, which could impose negative implication on productivity. However, In order to receive the maximum financial benefit, the trade-offs of how to apply the appropriate level of automation has to be carefully planned in an early stage. Automation technology can potentially improve operational safety by removing humans from hazardous working environment. Especially in those that involve toxic chemicals and high risk of injury or fatality. Sometimes, automation becomes an absolute solution. For scientific expedition purposes, to explore Deep-sea or outer space, these type of tasks will be hard to accomplish without adopting automation and robotics. On the other hand, there are also tasks that can be performed either by human or robot, such as lifting, cleaning, delivering, and many more. In this case, the designer has to be aware of which task is performed better by a robot than human and those tasks performed better by human than robot. Additionally, the designer should know on which tasks a human and a robot can complement each other to achieve the optimum result (Price and Pulliam, 1982).

The second question is how to define the optimum level of automation. Automation can be identified as a device or system that carries out a function fully or partially, with or without human intervention (Parasuraman and Riley, 1997). In general, work efficiency can be achieved by implementing a robot and automation process; however, increased automation levels can be very costly. Therefore, cost-effectiveness is another major consideration when deciding the optimum level of automation to adopt. Theoretically, most of the functions can be automated, yet the different level of automation could generate different effectiveness and cost. It is difficult to compare between the costly solution and the more cost-effectiveness one in terms of reliability and performance. For instance, producing a different type of product, manufacturers may demand different levels of KPIs for the automation strategy. Some may value production speed over quality, and some may prefer quality to quantity. The choice depends exclusively on the demands of the stakeholder on how to perform a particular job, the expectations of the product and these specifications will affect the KPIs of the automation scheme. In this dissertation, The author would like to refer to automation as the strategic distribution of the device or a system to partially or fully replace a function used to be carried out by a human. However, to emphasize HRC and human-robot interaction (HRI), to define how much human and robot effort should contribute either separately or collectively to achieving the job efficiently and economically (Steinfeld *et al.*, 2006). The levels of automation can be reflected in a variety of levels. As shown in Table 11, the automation levels are divided into ten scales.

Table 11: The automation levels, according to (Parasuraman, Sheridan and Wickens, 2000).

10 (High)	The robot /computer decides every function, activity, acting autonomously, neglect human interaction
9	Informs human only if the robot /computer decides to
8	Informs human only if the robot/computer asked to, or
7	To carry out task automatically then informs human only when it is necessary, and
6	Allow human a limited time to the response before automatic execution is carried out, or
5	To execute the human suggestion upon approval, or
4	To suggest an alternative based on the human decision, or
3	To narrow down the selections down, or

2	The robot /computer offers a complete set of decision/ action alternatives, or
1 (Low)	The robot /computer offers no assistance: a human must decide all decisions and actions

System designers need to be aware of the relationships and trade-offs between automation levels and human factors because in many industrial operations it is essential to integrate humans into the system engineering. In fact, humans make a special contribution to the automated system, and cannot be directly compared with robots. However, robots now can carry out many tasks once performed by a human, but human possesses unique properties that the robot will find hard to complete. there are also limitations restricts human capabilities. This also raises engineering concerns, human and system needs to be matched from an engineering point of perspective to optimize system design. An optimal match between humans and robots can be reached by exploring the functions of allocation between humans and robots. The rationale for the allocation of functions is not only to evaluate the discrepancy between human and robot performance, but also large numbers of social, psychological, and cost factors need to be taken into consideration (Price and Pulliam, 1982). A lesson can be learned from seeking a similar case in another field. Many studies have been conducted related to the allocation of function between human and machines. Interestingly, early studies tend to focus on aircraft cockpit, spacecraft, and air traffic control. In those studies, the Applicability of Adaptive Human-Machine Interface (AHMI) was emphasised (Sheridan, 1998). The author has carried out thorough studies on the applicability of distinct techniques to determine the distribution of tasks between human and machine. Robots in many aspects are superior to the machine, however, this type of studies was mostly conducted based on human-machine design issues. There is insufficient research data with regards to the allocation of functions between robots and human that can be used as aspiration. Consequently, the objectives of this part of the research consisted of the evaluation of the principal concepts of the selected methods, to discuss the benefits as well as constraints of the methods, and to analyse which combination is to be best suited to the characteristics of OCR.

One of the early and most controversial methods is the “List approach” proposed by Fitts in 1951. The “List approach” identified the relative abilities of human and machines. The aim is to compare the functions for which humans are more competent with machines to which task the machine is superior to humans. This method provides a quantitative measurement of the obsolete core performance areas, which are comprised of Sensing, Interpreting, Information Processing, Decision Making, Controlling, Monitoring, and Information Storage (Price and Tabachnick, 1968). By analysis the human and machine capability within the core performance area, the method claimed to use machine and human to do what function they best suit for respectively (Fitts, 1951). Yet other researchers have challenged the comparability of human and machine by the argument that human and machine is not comparable, instead, the correct method should be focused on how to embrace their strengths and to mitigate weakness by complementing each other. Understanding the specifications of the given task should be the first priority when considering the allocation of the task to human and machine. Then, based on the nature of the task, one should evaluate the most efficient distribution ratio between human and automation in order to accomplish the task.

The Human Effectiveness Function Allocation Methodology (HEFAM) concept was originally developed to formulate a system cost-effectiveness ratio that is used to measure the allocation of functions. Later, the development direction was shifted to evaluate personnel performance effectiveness (PPE). The cost-effectiveness alone will not be able to determine the accurate allocation of function. The PPE measures the relative ability of a human operator to perform a function adequately and to accomplish the task. The PPE date will be used together with system performance effectiveness to determine the overall system effectiveness. This method provides a methodology that includes human factors in the development decision-making loop. It considers many factors, such as humans, machine effectiveness, and cost analysis, in order to offer a systematic measurement of man-machine allocation. The limit of the method is that human-effectiveness data is very dynamic and difficult to acquire so that only estimated data is available. Alternatively, it is limited to identifying variables that influence human-effectiveness ratio and dividing them into soft and hard categories. The soft variables can be enhanced through training or other types of human efforts. The hard variables can be improved through reengineering either to improve the existing system design or to propose a new system. Hence, the HEFAM and PPE demonstrate that to optimize the allocation of functions only to compare human and machine capacities are not enough, but most importantly one must understand the reason behind factors that hinder either human or machine performance (Connelly and Willis, 1968).

The Systems Analysis of Integrated Networks of Tasks (SAINT) uses network modelling and simulation techniques to solve the allocation of functions between human and machine. Network models are constructed with a range of tasks. The tasks are categorised based on human capability in accomplishing each of those tasks. SAINT describes a process in steps that each step will be represented with a specific task. The relationship between these tasks can be defined by branching, time, and operator characteristics. There are several advantages of the SAINT method, first, the modelling and simulation process is relatively simple since no programming knowledge is required. Most of the data is collected in text format. Second, it is able to collect statistics on operator idle time, busy time, and the total time of the entire task process. The limitation of SAINT is that the model cannot handle multiple processes, functions or operators simultaneously. Instead, these data need to be collected individually (Price and Pulliam, 1982b).

Price-Tabachnik Descriptive Procedural Model was developed as a procedural model for determining optimal human performance in the aerospace program. The method offers an analytical procedure to determine what is the optimal role of human and allocation of functions throughout system development. In principle, first, in relation to the activities, human roles will be defined. Then depending on the identified dome-shaped, the optimal allocation of functions can be determined (Sheridan, 1998). The listed activities can be seen in Table 12.

Table 12: Activities in the Price-Tabachnick Approach to the Allocation of Functions, according to (Price and Tabachnick, 1968).

Activities in the Price- Tabachnick Approach to Allocation of Functions
Activities for determining the optimal role of man

Activity 1	Hypothesize the Potential Basic Role of Man	To hypothesize the fundamental role of the human in an action. By doing so, the activity that can only be performed by human will be decided.
Activity 2	Hypothesize Potential Complementary and Support Role of Man	To hypothesize the potential involvement of human in a task, and to analyze what is the complementary factors once the human role is to be considered an integral part of the system design.
Activity 3	Review Manned System Solution Feasibility	To assume if the human has to be included in the system, is there any causes that may impose a negative impact on overall system performance. If so, the infeasible manned solution shall be rejected.
Activity 4	Develop a Preliminary Crew Concept	To estimate the optimal crew size, training, and engineering skills in order to accomplish the task.
Activity 5	Analyse Personnel Support Requirements	To explore how to enhance the concept that developed in activity four by either provide user-friendly design and optimizing infrastructures that facilitate human activities.
Activity 6	Review Potential Crew Role for Acceptance and Reliability	To review the variables that could influence human performance in the given task, and compatibility between human capability and technology.
Activity 7	Synthesize Optimal Crew Role	To surmise the previous activities and to determine the optimal combination.
Activities for determining the optimal allocation of functions: The rest of the activities determines the allocation of function by defining what specific performance that requires from a human if the human is considered to be included in a system.		
Activity 8	Establish the Feasibility of Man-Rated Allocation	To identify the potential man-rated allocation that is not feasible to human. Man – rated allocation include tasks such as to use human as an operator, inspector, supervisor, and controller.
Activity 9	Develop Potential Man-Rated Allocations	Based on the result from activity eight, which assigns the allocations that augment both human and machine.
Activity 10	Review Allocation Potential Against Psychophysical Capacities	To evaluate human limitation by study the allocation potential against psychophysical constraints of human.
Activity 11	Review Allocation Potential Against System or Function Constraints	To review what type of performance constraints that man-machine system will impose to a human worker.
Activity 12	Review Allocation Potential Against Human Reliability	To evaluate what rates of human errors can influence the potential allocation functions, and to identify human reliability in the system.
Activity 13	Synthesize Man-Rated Allocations	To capture the prior operations and rank the candidate man-machine allocations for each system feature.

Price-Tabachnik Descriptive Procedural Model approach has been recognized as one of the most comprehensive descriptions for carrying out allocation exercises. Yet it still experiences lack of data during the allocation process, for example, the activity twelve the human error data is often unavailable from the industry. All in all, the author has conducted detailed research based on limited literature sources, although the aforementioned models, methods for determining the allocation of functions between humans and machines, automated systems were developed for other industries. The next step will be to investigate which one of combinations of model and methods are applicable to the OCR system design. Due to the unique character of the construction industry, it is important to be aware of the fundamental difference between industrial and construction operation and tailoring a system that is suitable to the construction industry. In addition, some related questions need to be raised. First, how does automation and robotics influence human attitude and motivation? Second, how can the skill gaps imposed by implementing automation technology be fulfilled? Third, how can the construction industry be convinced to adopt automation technology and to make changes collaboratively?

2.5.3 Manufacturing versus construction

Automation and robotic technologies are often referred to as a solution to solve many profound industry-related issues, such as declining productivity, skilled labour shortage, safety, and quality. In principle, some construction processes can be automated while others not, even the one that can be automated in the manufacturing process might not be realised in the construction context. The construction sector is fundamentally different from that in the manufacturing sector in many aspects. The difference can be reflected in the following characteristics including working environment, distribution of materials, the allocation of physical force, skill sets, and information transformation, see **Error! Reference source not found.**. Noticeably, the construction process is more complicated in manufacturing than in terms of working method, procedure and skill requirements (Everett and Slocum, 1994). The other differences between the two industries can also be found in design, process, fabrication education, and training perspectives. In addition, it is important to understand which types of construction task or part of the processes are best suited for automation, and how to apply the appropriate level of automation and robotics once the types of the task have been identified.

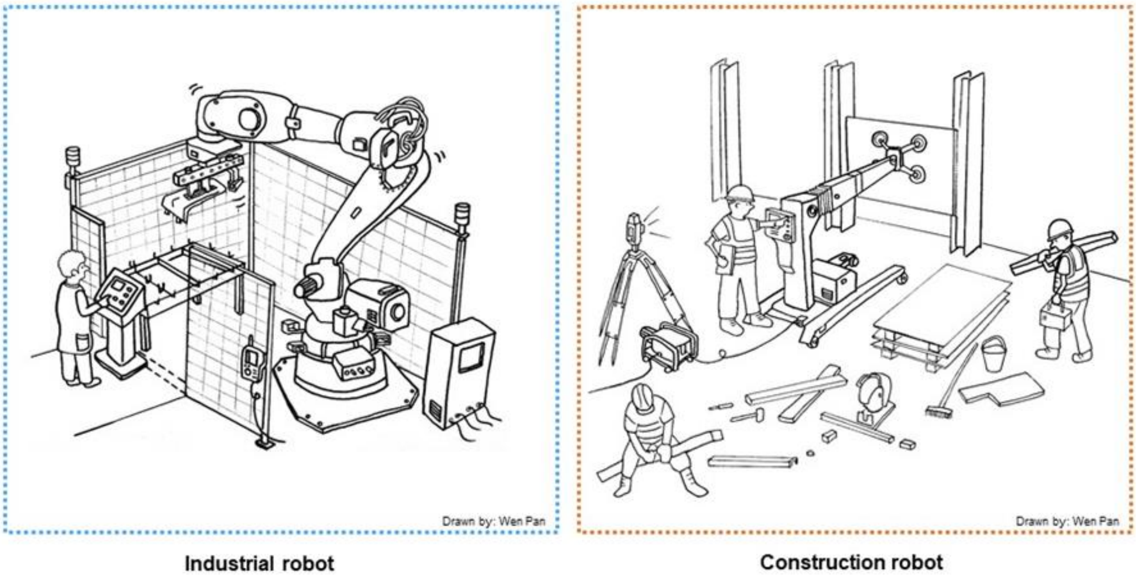


Figure 7: Industrial robot and construction robot, source: (Wen Pan).

In the manufacturing industry, most of the works are often carried out from an indoor facility where labour, production equipment, and robots are protected from the natural environment.

Products are manufactured in a controlled setting, while the logistics supply and work stations are predefined in the early stages, and human and robot cooperation is restricted in most instances due to safety measures. The industrial robots are used to carry out repetitive, heavy, and high-risk tasks to optimize productivity. Industrial engineers often divide the manufacturing process into elemental motion levels. Two of the most influential elemental motion levels are the "therbligs" method and the method-time measurement (MTM) method. The "therbligs" method has divided human motions into numbers of components, such as reach, grasp, and lift (Gilbreth and Lilian M, 1924). The MTM method defines human moments that are required for the production activities into several classifications. A set of time has assigned to each motion to measure the overall time required to complete the entire task (Gomberg *et al.*, 1949). With an understanding of the basic movement required to the task, the production engineer could optimise the production sequences by either changing production technology or allocating labour. These two methods are wildly adopted in manufacturing (Everett and Slocum, 1994).

The product designers, process engineers and the production engineers are working closely to share a common goal, which is to produce as many products as possible by using the available resources, yet maintain good quality as well as health and safety. This level of comprehension between designers and engineers has been achieved by complying with the industry standards, and vocational training. The modern manufacturing industry has adopted numbers of production ideologies, such as lean production, Design for Production (DfP), Design for Assembly (DfA), and Just in Time (JiT), these ideologies have a huge impact on product design, production, assembly aspects, and influenced the manufacturing industry globally. Lean manufacturing is a production concept developed by the Japanese automotive company, Toyota. Lean manufacturing focuses on waste reduction by addressing seven types of waste, often identified with the acronym "TIMWOOD": Transport, Inventory, Motion on, Waiting, Overproduction, Over-processing and Defects. Reducing one or more of these types of waste enhances productivity while simultaneously cutting production cost and time (Iuga and Kifor, 2014).

DfP strategy refers to a strategy, which adjusts design and production parameters to each other so that a product can be efficiently manufactured. DfP addresses different types of production issues during the design stage, such as the product size, the type of production (e.g., flow production, shop floor production), individual production processes, throughput times, logistics, supply chain design and degree of automation. If DfP is principally concerned with making individual parts as easy and cost-effective to produce as possible, then DfA strategy focuses on the methods of assembly for the produced parts as well as the minimization of assembly costs. As the parts are integrated into complex components, assembly is often just as critical as the production of parts (Boothroyd, 1994).

The JiT strategy is employed in the "Pull" production model. "Pull" means that the quantity and quality of products manufactured depend on the customer's demand. A JiT inventory would contain only the material necessary to produce the products asked and would be constantly restocked in step with the production sequence, hence minimizing the storage space (Salem and Zimmer, 2005). Evidently, the manufacturing industry has developed highly standardized methods in the areas of product design, production and logistics that are supported by a mature market. The infrastructures are efficiently distributed, the labour forces are highly qualified, and the supply chains are centralized. Combined with the recent technology implementations such as the Internet of Things (IoT), automation, robotics, and machine learning, which facilitates the manufacturing industry to become a highly sophisticated industry.

The construction site is often exposed to the elements such as rain, snow, wind, and sun. Under bad weather condition, it can be a very hostile environment for labour. Commonly, workers and equipment are moving around either inside or outside the product, in this case, the product is to be referred to as the building. Many construction tasks are repetitive, yet the construction process is rather dynamic, in which many tasks are carried out by several trades in parallel. An experienced construction craftsperson requires many years of training and experiences in order to conduct a specific construction task satisfactorily. The craftsperson is typically required to understand the instruction either verbally or through reading a drawing from the client. Then based on the characteristic of the task he/she must able to plan the work accordingly by considering the appropriate tools, materials, and method will be used. While performing the work he/she must manoeuvre around the worksite and try to avoid any obstacles and time waste on searching for tools or replenishing materials. Nevertheless, most importantly, the finished work must reach customer satisfaction. Construction work can be defined as various cycles, within each cycle there also consists of several general tasks. For example, bricklaying has been considered to be physically demanding, which also contains repetitive elemental motions. The main objective of bricklaying is to complete laying bricks to the required line, level, elevation, and aesthetics according to the architectural design. The required tools and equipment are basic hand tools, wheelbarrows, tape measure, block cutter, cement mixer, levelling kit, trestles and boards, and safety equipment. After the foundation is set, first the bricklayer will mix the mortar according to the manufacturer’s instruction. Second, trowel the right amount of mortar on to the right location of the bricks. Third, lay the bricks based on the correct bonds. While laying bricks the bricklayer must make sure the courses are level. In case if it is not level, a genital force will be applied to ensure all bricks are lined up. Once all courses of bricks are straight, level, and plumb, the bricklayer will finish off the work by placing the desired amount of mortar to both vertical and horizontal joints, and then clean off any stains and make sure the joints are smooth with a brush. Bricklaying is a relatively simple task when compared with other more complex construction tasks such as welding or carpentry work, yet the work still requires a substantial amount of human interactions like decision making and information processing. Ensuring a correct ratio of sand, water and cement for mortar mixture, and the choice for bonding styles, even the amount of mortar to apply onto each brick requires experience and correct judgement from the bricklayer.

The collaboration between architects, structural engineers, quantity surveyors, local authorities, contractors, and the client are somewhat rudimentary, fragmented, and regimental. An architect uses the customer's design brief to design the interior layout, exterior and building functions. The finalized plan will be submitted to a local planning department for approval. The structural engineer will solve any issues that are related to the structural soundness of the building by providing specific structural calculations, technical advice, and liaising with relevant professionals such as the architect and contractors. The structural engineer will submit designs that describe to the building control department how the proposed building will be erected. The submitted design must comply with the building regulation. The quantity surveyor typically is in charge of cost-related issues that are associated with the construction project. The main duty of a quantity surveyor includes conducting a feasibility study, estimate material, labour cost, preparing contracts, and advising on legal or contractual issues. The local authorities will evaluate the submitted documents and decide whether or not to grant planning permission or building regulation approval. Contractors will commence the work on-site once the necessary permissions have been granted. The contractors will specify work plans, construction methods, materials, and liaising with the architect and structural engineer. It is clear that architects, structural engineers and quantity surveyors who masterminded the proposed end-product, will not necessarily get involved with the building process. The client and the planning authority is not interested in understanding the constructability of the building that has been approved. In a way, in the construction industry, the product design procedure is independent of process design, yet process design is closely linked with fabrication activates. Thus, there are two main forms of fragmentation in the construction industry as described above; internal and external fragmentation. The internal fragmentation refers to brakes down in communications between the internal consortiums. The external fragmentation refers to insufficient coordination between authorities and regulators (Abadi, 2005). Consequently, each project stakeholder acts as an individual separate entity from the others, hence, there is no overall management and coordination throughout the planning, designing, procurement, fabrication, installation, and the inspection process (Tenah, 2001).

The construction industry is a complex and dynamic industrial sector. In many aspects, it is fundamentally different from the manufacturing industry. In regards to the construction industry, the end product often refers to as the building, even the design of the building is identical, yet the construction approach and material selection could vary that subject to many external influences such as local regulation, site condition, availability of technology, and competences of the craftsperson. On the other hand, most of the consumer products are mass-produced followed by the same design specification, production method, and managerial principles. The construction industry is fragmented in terms of communication, collaboration, and motivation. In contrast, the manufacturing product designer, production manager, and process designer are usually employed by the same firm. The product designer not only designs the final product but also specifies the processes and technology to be used to produce the product. The process designer not only determines the production process but also works closely with the product designer and provides advice on how to increase productivity from a product design perspective. By studying elemental motion, adopting innovative technologies, and reducing information contents from work, the industrial engineers will able to simplify production sequence, reduce labour-intensive tasks, and augment human performance. Due to the increasing level of automation in the manufacturing process, less human physical and mental interaction is required, thus less training is necessary for the new employees. When entry skill requirements are lower, ultimately the recruiting process will be eased. However, in construction, many tasks contain physical equipment and information components. Physical components refer to human contributions such as physical strength, flexibility, decision-making, and learning ability. Equipment components consist of hand tools, power tools, automated equipment, and construction robots. Information component comprises of design data, building specification, construction plans, and instructions. The information is available in many forms, such as handwritten, hard copy, and digital. Accomplishing the construction task successfully depends on a well-balanced contribution between human, equipment and information component.

As discussed above, the author analysed the differences in design, process, fabrication, working environment, and collaboration between construction and manufacturing. Evidently, it is hard to directly copy the success story in terms of adopting automation and robotic technologies from the manufacturing industry and to expect it to work in the construction industry (Everett and Slocum, 1994). It is unlikely that any time soon the architects, structural engineers, construction product, process designers, and contractors will coordinate to the same extent as in manufacturing. The interface between construction product, process, fabrication design and robotic technology need to be narrowed down. Encouragingly, for the past 35 years, researchers and companies globally have been working on the topic. The next chapter will present some of the early examples of OCR and site automation, explore state-of-the-art techniques, assess the difficulties facing innovation in the construction industry and suggest the study hypothesis.

2.5.4 On-site construction robotics and site automation

Research institutions, universities, companies, and construction-related machinery enterprises in the developed nations have carried out construction automation and robotics R&D since the late 1970s and the early 1980s. Especially in Japan, robotics technology has played a significant role in the manufacturing sector, and robotics technology has contributed extensively to the country's economic growth. In the early 1980s, Japan's construction industry started to face a shortage of skilled workers due to the fact that working condition of conventional construction sites was considered dirty, dangerous and difficult by the young generation. The construction industry had begun to fall behind the manufacturing industry. It was thence essential to improve working conditions and productivity.

Active R&D initiatives were the focus of the main Japanese contractors to increase their competitiveness and increase market domination. The Japanese construction giants Shimizu, Takenaka, Obayashi, and Taisei have spent huge efforts in developing innovative construction technologies over the years. It was estimated the large contractors spent approximately 1% of its gross revenues on R&D activities, which is around $150 million each (Gann *et al.*, 1997). In 1978, the Japan Industrial Robot Association (JARA) established a research commission led by Professor Yukio Hasegawa that committed to R&D of construction automation and robotics (Bock and Linner, 2016). In 1983, Shimizu developed the world's first construction robot, "SSR-1" and its main duty was spraying fireproofing material on to steel elements, see Figure 7.

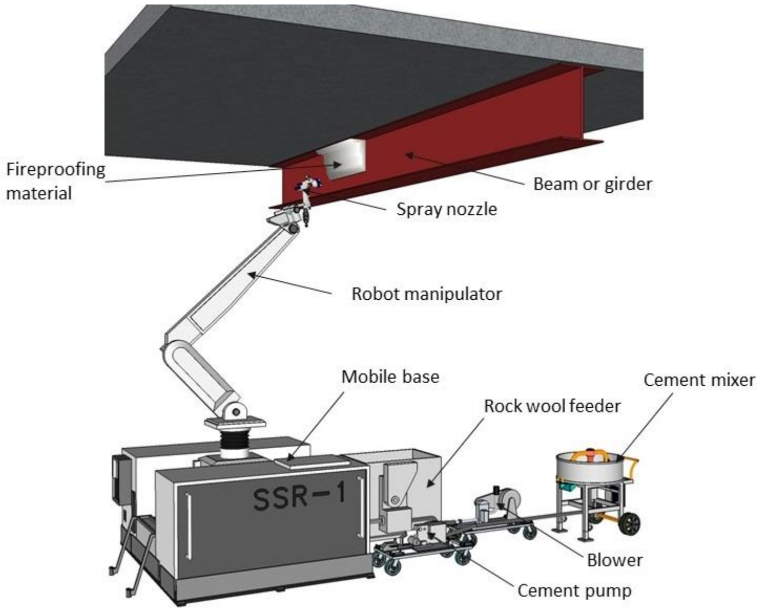


Figure 7: SSR-1 fireproofing spray robot, reproduced by (Wen Pan).

The "SSR-1" was the first robot to demonstrate the feasibility of using a robot on the construction site (Ueno *et al.*, 1986). In 1983, the Construction Robotic Investigate Committee was established by Architectural Institute of Japan (AIJ), and in 1987, the Need for Construction Robot Users" investigative group was launched by the Building Contractors Society (BCS). In 1990 and 1992, the AIJ released analysis reports of "Robotic Technology for Building Production" and "Construction Automation", respectively. Until today, there are over 150 single-task construction robots (CICs). Most of the systems were developed to be used on the construction site. Each type of robot was designed to focus on a particular on-site work task. Robots are normally designed and developed by the end-users in collaboration with manufacturers and further improvement of the robot is commonly realised after an on-site demonstration. The increased popularity of robots is expected with improved economic incentive and wider applicability (Leslie and Nobuyasu, 1998). The STCRs can be categorised as 24 types according to the Cambridge Handbooks in Construction robotics. In Table 13 below, one representative system is selected to demonstrate each identified application type.

Table 13: Brief description of the STCRs based on their application, according to (Bock and Linner, 2016)

Application type	Robot name	Developer	Brief description
1. Automated site measuring robot	Irma3D (An Intelligent Robot for Mapping Applications)	Robotics and Telematics, University of Würzburg/ Automation Group, School of Engineering and Science, Jacobs University Bremen GmbH	Inspection, surveying of historic buildings for preservation and renovation purposes (Nüchter, Elseberg and Borrmann, 2013).

2.	Earth and foundation work robot	Automatic Digging and Soil Removing System	Tokyu Construction Co., Ltd.	Excavation, material delivery, and special end-effector to break up compacted soil elements.
3.	Robotized conventional construction machines	Centaur (Articulated Hauler)	Volvo Construction Equipment	A concept articulated vehicle with a modular design that offers maximum flexibility, functions durability, and intelligence.
4.	Reinforcement production and positioning robot	TRFR-01 Reinforcing Bar Fabrication Robot	Taisei Corporation	Fabricate steel reinforcing bars on-site semi-automatically.
5.	Automated/ robotic on-site concrete structure production	Gantry-Type Contour Crafting Robot	Behrokh Khoshnevis, Center for Rapid Automated Fabrication Technologies (CRAFT), University of Southern California	Contour crafting technology by using special end-effector that deposits additive materials, and shape the deposited materials into final form by using custom-made trowels (Khoshnevis *et al.*, 2006).
6.	Automated/ robotic on-site steel assembly on-site	Truss assembly robot	NASA Langley Research Center, W.Doggett	To assemble complexed truss space structure under lab condition.
7.	Bricklaying robot	SAM (Semi-Automatic Masonry System)	Construction Robotics	To pick and place, spread mortar, and position brick in conjunction with human labour.
8.	Concrete distribution robot	Automated On-site Concrete Logistics System	Konoike Construction Co.Ltd.	Distribute concrete material for high-rise building or large working areas.
9.	Concrete levelling and compaction robot	LOM10 Screeding Robot	Lomar SRL	The automatic mobile track-based concrete screeding robot with a laser guidance system.
10.	Concrete finishing robot	Mobile Floor Finishing Robot	Obayashi Corporation	Automatic floor finishing robot for large open areas with the ability to navigate around obstacles.
11.	Site logistics robot	AGV for Construction Sites	Kajima Corporation	AGV equipped with forklift type material handling system travels on fixed trajectories.
12.	Aerial robot for building structure assembly	Aerial Construction with Quadrotor Teams	GRASP Lab, University of Pennsylvania/Q. Lindsey, D. Mellinger, V. Kumar	A swarm of aerial robots that designed to pick up, transport, and assemble the predefined structural elements (Lindsey, Mellinger and Kumar, 2012).
13.	Swarm robotics and self-	Automatic Modular Assembly	Y.Terada and S.Murata, Tokyo Institute of Technology	Robotic arm interacts with standardized block elements that

assembling building structures	System (AMAS)		featured with robotic property (Terada and Murata, 2008).
14. Robots for positioning of components	Mighty Jack, robotic crane end-effector	Shimizu Corporation	Mighty Jack is a custom-made crane operating end-effector that developed to position steel beams.
15. Steel welding robot	Steel Column welding Robot	Obayashi Corporation	The STCR is developed as a sub-system of the Automated Building Construction System (ABCS). The system is used to weld joints between steel columns.
16. Façade installation robot	Mighty Hand, concrete panel installation robot	Kajima Corporation	Semi-automated concrete panel installation robot equipped with five DOF, that able to handle, position, and place heavy concrete façade panels.
17. Tile setting and floor finishing robot	Mobile Robotic Tiling Machine	Future Cities Laboratory (FCL)/ROB technologies AG	The STCR is developed as a prototype to automate tiling process. The system is equipped with an automated adhesive deepens system and pick and place robotic manipulator.
18. Façade coating and painting robot	Exterior wall painting robot	Taisei Corporation	Fully automated external wall painting robot is developed to travel on an integrated guide rail of a high-rise building.
19. Humanoid construction robot	HRP Robot Series	Kawada Robotics Corporation, AIST, NEDO, MSTC, METI, Yasukawa, Shimizu Corporation, Honda	A joint venture project between many companies that provides humanoid robot to assist on-site tasks, and working alongside human worker.
20. Exoskeletons wearable robots and assistive devices	FORTIS	Lockheed Martin, US National Centre for Manufacturing Science	Mechanical, lightweight exoskeleton system that assists worker to handle heavy construction tools and materials.
21. Interior finishing robot	Mobile Drilling Robot	nLink AS	The STCR is designed to measure, position, and drill holes in the ceiling for electrical ducts (nlink, 2019).
22. Fireproof coating robot	SSR1-3 Series	Shimizu Corporation	Automated fireproof coating robot for overhead steel beams or girders. The robot is able to adjust the position according to several of ceiling height, and structure features.
23. Service, maintenance, and inspection robot	SIRIUS, the façade cleaning robot	Fraunhofer IFF	SIRIUS is designed to clean high-rise building curtain wall elements. It equipped with cleaning end-effector and hoist by an overhead hanger (Fraunhofer, 2019).
24. Renovation robot	Asbestos removal robot	Taisei Corporation	The robot is able to remove, collect, and package asbestos via a remote control system.

In general, most of the STCR usually consists of three main components: a travel platform, a manipulator and an end-effector. The STCR is normally a stand-alone system that is developed for a specific task, which reflects a practical need of the construction practitioner and to be operated under a coordinated environment. This means, the system is developed for a unique circumstance and it is difficult to be implemented in a task or situation, which the original design is not derived from. From the analysis of the operation process of the selected STCR, it is evident that the size and weight of the system are very large, which were difficult to be transported by material lift, very often, the system has to be disassembled and reassembled once it arrives on-site. The STCR must be simple to use and cost-effective. This imposes some challenges to the system designer. The most effective method to achieve this design goal is to reduce the automation level of the robot. However, once the robot has less automation, the operating environment must be compatible and robot-friendly, so that the robot's awareness, technical specification and cognitive behaviour are not as high as when fully automated. The drawback of this method is that the operational ambient environment needs to be well organized and equipped with appropriate sensors or hardware to assist the robot operation. A longer on-site setup and calibration time may occur. Thus, it is correct to consider that STCR can outperform human labour items of time-saving and offers consistency in quality, however, the payoffs and gains are offset by the additional tasks required to set up, calibrate, and operate the robot.

In the later 1980s, after experimenting STCR on-site, Many contractors also recognized that it would be difficult to enhance the general efficiency of building duties and achieve maximum payoffs unless they understood the building manufacturing principle, and to automate all or part of the construction process. The main reason for this difficulty is the complexity and variety of the buildings themselves, the engineer and manual labour organizations, and the environment in which buildings are constructed. In the early 1990s, the Japanese construction industry is starting to experiment with automation in the entire construction process, often referred to as integrated construction automation system, or a Super Construction Factory (SCF), with aims to improve on-site safety and efficiency and minimise manual activities (Leslie and Nobuyasu, 1998).

Integrated construction automation systems contain four fundamental components:

- Full weather-proof on-site factory
- Automated jacking system to allow the on-site factory to climb up
- Automated material handling system
- The centralised on-site integrated control system

The fully enclosed working platform provides factory-standard working conditions where STCR, material handling systems and other automated construction equipment can operate. Most of these on-site factories use JiT principles for the delivery of materials. Radio-Frequency Identification (RFID) has been used for tracking and placing materials and eased on-site robot operation tasks. The entire platform is erected on a hydraulic jacking system. Once construction work is done on one floor, the platform will be jacked up to the next operation location. The central control station monitors and controls all construction processes in real-time:

specifications of all building components and working drawings are both stored by computers, and work schedules can be programmed using current data thereby optimizing on-site productivity. Many automated construction systems have been developed; the most influential case in the field will be detailed below.

The Shimizu Manufacturing System by Advanced Robotics Technology (SMART) system was the world's first automated construction system to be applied to a full-scale building project Figure 8. In 1991, the Juroku Bank Building was the first building erected using an automated system on-site. The building was a 20-story steel-framed structure, and construction was completed within three years. The on-site factory rested between structural beams and columns; it had been assembled on the ground floor and was then jacked up floor by floor by using an Automated Jacking System. The automated material handling system consisted of both a vertical and horizontal delivery system (cranes and lifts), which delivered building components from the ground factory up to the installation level then aligned and positioned the building components to the right location by their identifying RFID bar code. The steel beams and columns were specifically designed for automated assembly. Once the column was in place, the system would automatically measure the thickness and align the beam into position. The single-task welding robot-welded column joints according to the database and the instruction from the laser sensor (Martinez *et al.*, 2008). The computerized information management system monitored and coordinated the construction process. It kept a running inventory of building materials, working drawings, scheduling, and progress. In real-time, it monitored crane operations and the volume of completed tasks. Integrated computer programs recorded labour, safety and quality control issues (Linner, 2013).

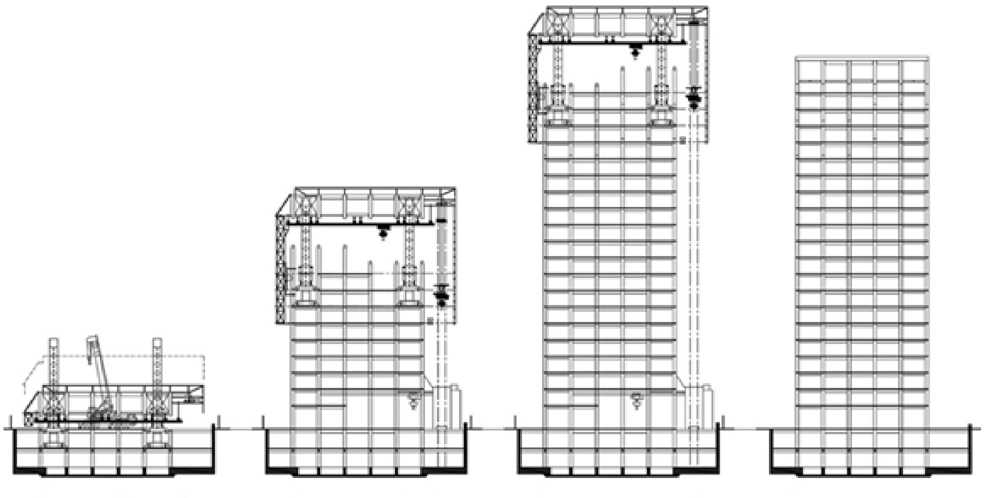


Figure 8: Smart system construction procedure, reproduced by (Wen Pan).

The SCF can effectively integrate various types of STCR on-site that enable synchronisation of many construction tasks. Hence, the implementation of SCF can reduce construction time, improve on-site operational safety, and enhance the productivity of the construction process. Although, SCF still imposes some challenges that hindered its commercial success. First, the weight of the SCF can be very great, which means the building structure and the self-climbing systems are customs made to withhold the enormous weight. Some subsequent systems are considerably lighter, but still, need unique consideration when designing the building's load-bearing structure. Most of the SCF is custom-designed to erect a certain building type. For example, SMART can only erect steel frame structure, and Big Canopy developed by Obayashi Corporation in 1995 is designed to handle precast concrete structure. Internationally, there are not many buildings that were designed with such requirement, so that SCF is only compatible with few construction technologies. In addition, the investment cost of SCF is tremendous and often shared between numerals of companies, research institutions, and universities. In summary, high investment costs, low flexibility, and low compatibility with the existing construction method and materials were the reasons why the SCF concept did not scale up and experience economic success.

Robotics and automation technologies are still relatively new to the conventional construction industry. The construction industry is unfamiliar with the process and methods that are required to adopt such technology. The infrastructures that support the technology have not been developed so that it is difficult to introduce construction robotics or automation to the conventional construction filed. In 1988, Prof Thomas Bock proposed the notion of Robot-Oriented-Design (ROD). The essences of ROD expresses that the architectural design should not only focus on the aesthetic aspect of the building, but also should consider construction method, running cost, serviceability, maintenance, and geometrical composition of the building. The concept emphasizes the principle that, in order to be able to successfully implement robotic and automation technologies on-site, building design, production, on-site assembly, and operation must be considered from an early stage (Bock, 1988). When considering adopting robotic technologies, the building designer must adjust the conventional manual-oriented thinking to the ROD method, must consider how to design a building and create an on-site environment that is easy for robots to operate. There are a number of methods suggested by Prof Thomas Bock that can transform the conventional construction method to the ROD construction method. He mentioned that the current building market is lacking sufficient quality control system, the state of the art technologies are unevenly distributed between small and large enterprises. It is important that each party involved in the construction project is working closely with each other and defines the design features of the building components, assembly sequences, construction methods, technology requirements, and software applications cooperatively. ROD concept requires the building system to be designed by using standardised components that are compatible with robotics operations, in here robotic operations can be defined as off-site manufacturing and on-site assembly. It is crucial to formulate a clear product hierarchy structure that systematically divides building parts, units, and components into hierarchical levels based on the ROD specification and requirements. Subcomponents are preassembled off-site and to be shipped on-site in the later stage. In a way, the construction site becomes the last stage of the construction process, where preassembled building components are finally assembled on-site. Low accuracy also is another common issue associated with the construction sector. For human labour, minor imperfections and tolerance can be easily addressed manually. However, even though a robot can recognise and operate in unstructured condition, ultimately this will increase the robot complexity, hence increase the costs. Prof

Thomas Bock advised a range of methods to solve this, and can be summarised as below, also see Figure 9, Figure 10;

- To reduce temporary building elements, structures, and support.
- To simplify the building element designs by using symmetrical, and\or asymmetrical methods.
- To use a compliant design principle, so that the tolerance margin has been considered during the early design stage.
- To consider a joint method of the building elements, with the aim of avoiding geometric error during assembly.
- To engineer the building elements that reduce misalignment and inaccuracies
- To design a building element that contains a feature that will ease on-site assembly
- To reduce the existing redundant parts according to the ROD principle by reengineering

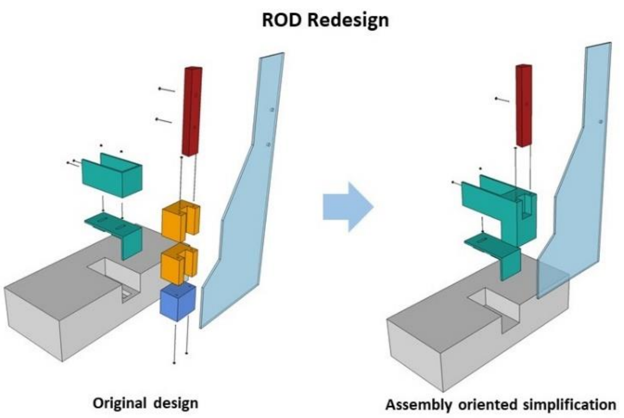


Figure 9: Assembly oriented simplification, according to T. Bock.

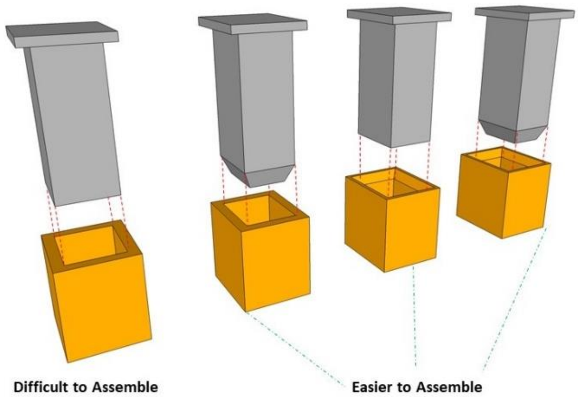


Figure 10: Building elements are designed to ease on-site assembly, according to T. Bock.

The ROD concept later served as the principle for automated construction and robot-based construction sites around the world. The biggest challenge of implementing ROD in the construction industry includes convincing the conventional key stakeholders to adjust to a new way of design, production, and management strategy. Unfortunately, because of the conventional construction industry. There are very complex supply chains and firmly established organizational methods that are very often reluctant to change. Based on the experience of the CIC project, the author will propose a practical strategy that can progressively transfer the construction industry to commit to the ROD fundamentals.

2.5.5 State of the art

Automation in construction and robotics has become one of the popular research topics recently, yet the topic itself has been investigated for more than 35 years. Despite the long R&D history and combined efforts between academics and industry practitioners, it is intriguing there is still a very small margin of on-site construction activates that were augmented by using STCR. Nevertheless, for a conservative, competitive and highly fragmented industry that is prone to be resistant to rapid technical evolution, it is encouraging to see continued movement and gradual attempt in adopting automation and robotics technologies. In this section, the author will provide a number of examples from research institutes, universities, and industry leader, as well as provide an insight into the systems that have been successfully commercialized. The selected examples will demonstrate the current research trends from a range of preventives. The selected commercialised systems will identify the features that conveyed by practical application and the design attributes that need to take into consideration when attempted for market launch.

In recent years, especially accelerated by Industry 4.0 Era, digital design and fabrication by using robotic tools to produce highly customized building elements both on-site and offsite become more feasible for architects. The following section will use some distinctive examples to give an overview of robotic fabrication technologies on contemporary architectural practice, design and teaching.

- On-site robotic construction: The project is funded by the Swiss National Competence Centre of Research (NCCR) Digital Fabrication project under agreement 51NF40-141853, in cooperation with ETH Zurich (Dörfler *et al.*, 2016). The project investigates semi-automated construction fabrication strategies for using a location-aware mobile robot that is equipped with customized end-effector, which allows the robot to allocate installation position and to pick and place the standard building block element in a specific predefined sequential pattern. This approach tests the adaptable, flexible assembly method by using autonomous robotic systems that potentially expand fabrication of large-scale building structure in an on-site condition, see Figure 11.

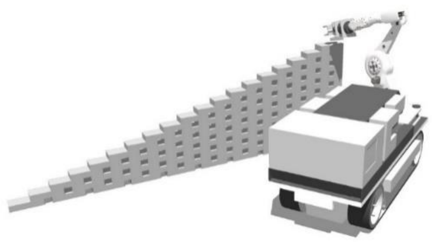


Figure 11: Semi-automated construction fabrication robot, reproduced by (Wen Pan).

- Exploration robotic fabrication and design education: The school of Architecture in Tsinghua University has conducted an experiment that integrates architectural design with robotic fabrication, digital design and assembly technologies. This is the first time the Chinese university attempted such cross-disciplinary teaching and training exercise. The training course was scheduled for 15 weeks; students were divided into three groups assigned with research topics and task description. Most of the students had no robotic programming or parametric design experience, therefore they had to be trained from scratch. They were equipped with KUKA KR6 900 robotic arm and ABB IRB4600 robotic arm and were taught how to use Rhinoceros, Grasshopper and parametric design platform to design, fabricate and assemble assigned architectural models. Several experimental attempts were made and achieved auspicious results (Philip F, Achim and Neil, 2015).

The examples below consist of academic research funded by the local government, the European Union (EU), and joint venture collaboration with the industries. Even though most of the projects, which are demonstrated below are still in the research phase, they have demonstrated vigorous efforts and a growing trend from both academia and the construction industry sectors that intend to develop practical OCR applications for the construction industry, see Figure 12.

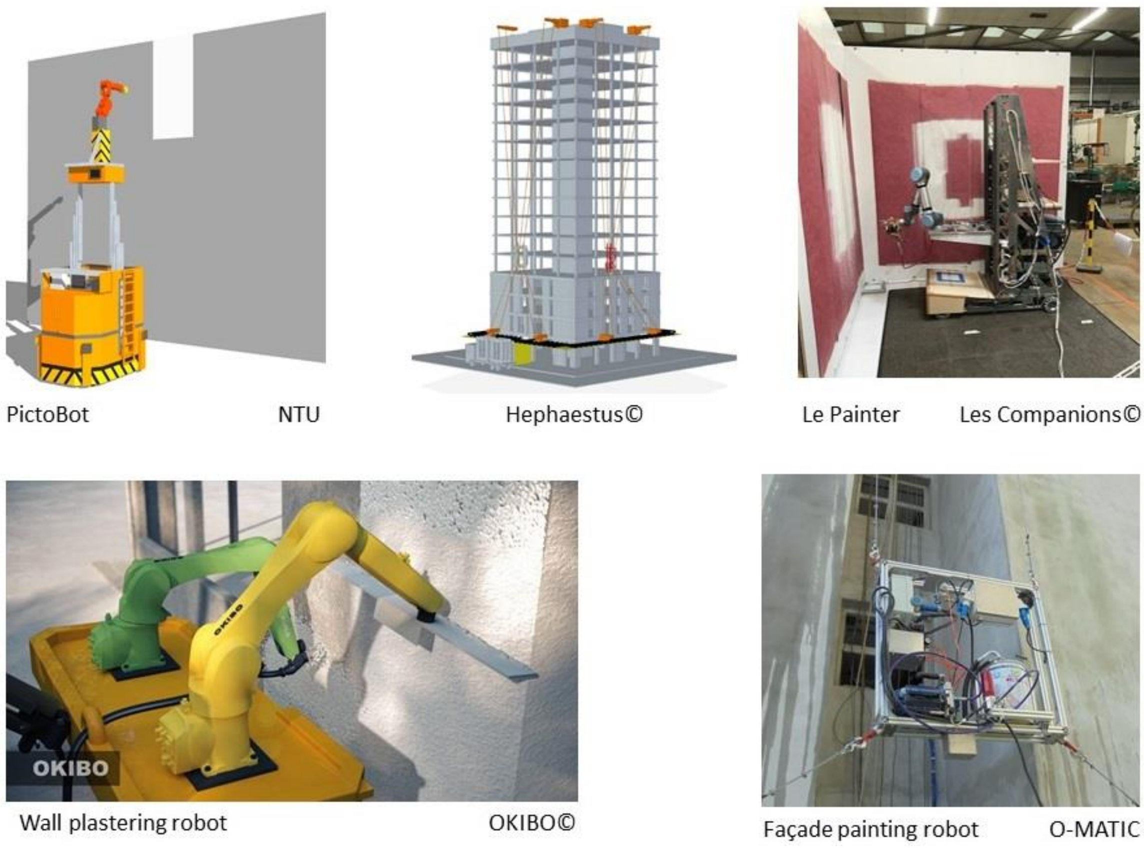


Figure 12: Examples of construction robotics products that still under development.

Academic and industry research efforts:

1. PictoBot: The robot is developed by researchers from Nanyang Technological University (NTU) along with JTC Corporation (JTC) working closely with a start-up company called Aitech. The robot is designed to paint interior surfaces with high elevations and high ceilings, such as warehouses, industrial buildings, and commercial buildings. The robot is equipped with a mobile platform, a six DOF robotic arm that has been adopted with a high precision painting nozzle, an automated scissor lift system, optical camera, and laser scanner systems. The key design goals are to save the robot 25% of the operating time compared to manual operation; the robot should be able to navigate and reach a height of up to ten metres; the robot should be able to adapt to different geometries; the system should be compatible with various commercial paint products; the robot should be designed to be able to operate under high temperature, humidity, and a fine dust environment. The robot demonstrates great potential to use robotic systems to paint large spaces; it is currently to be tested under the on-site condition and not yet commercialized (Asadi, Li and Chen, 2018).

2. Highly automated physical achievements and performances using cable robots unique system (Hephaestus): The Hephaestus project is founded in innovation and action scheme under the EU's H2020 Programme (H2020/2014-2020) under grant agreement number 732513. In the project, TUM along with the other eight partners are developing a solution that uses a cable-driven parallel robot that is equipped with modular end-effector to autonomously position and install a glazed curtain wall element. The flexible cables suspend the functional platform of the system, and the cables operate as actuators of parallel manipulators. A robotic arm with a modular end-effector and end-effector exchanging station is located on the functional platform. The system is designed to be able to pick up the curtain wall component, to drill holes in the desired position, to place installation bracket, to adjust installation position, and to install the curtain wall component in the correct location with minimal human intervention (Taghavi, Iturralde and Bock, 2018). The project is underway and the partners are presently designing a test prototype to be used for laboratory testing.

3. Le Painter: The Le Painter system is developed by Antoine Rennui from Les Companions, the main function of the system is to perform surface finishing processes of an interior wall either for a new project or for renovation purposes. The system consists of an AGV platform, a six DOF robot arm, and interchangeable end- effector that can switch between paining and grinding functions, control systems, power supplies, and positioning systems. The robot is operated by one operator and performs painting and surface preparation tasks for large open areas, whereas the corners of any spaces that are hard for a robot painting nozzle to access will be painted by the human operator. Hence, the most repetitive tasks are assigned to the robot and the tasks that require skill and decision making are given to the human worker. First, the human operator will conduct site observation to determine which area will be painted by the robotic system. Second, the positioning devices will be set up to assist the autonomous operation. Third,

the human operator will scan the operational space via a 3D scanner, and the information will be processed as special mapping data that assists the robot to paint and navigate in the space. Finally, the robot will be calibrated and programmed for further testing. Currently, the robot is in the prototype phase and is not yet ready for on-site operation (Les Companions, 2019).

4. Wall plastering robot: The robot is developed by OKIBO from Israel. It is a multi-functional OCR for interior painting and plastering. The robot consists of a mobile platform that enables the robot to travel in construction site condition; it is equipped with a modified six DOF industrial robotic arm along with a multi-functional end-effector that is designed for extraction and painting functions. The robot adopted a range of advanced sensor technologies such as a vision sensor, LiDAR sensor, and motion sensor that enables the robot to understand the surrounding environment and to conduct the assigned task accurately (OKIBO, 2019). The robot is in the prototype phase, the company aims to test the robot on-site in the next stage.

5. Façade painting robot: The façade painting robot is cable-driven, which operates on the building external façade. The system is developed by O-MATIC from Hong Kong. The robot is comprised of a painting nozzle, on-board airless paint compressor and power supply. The control unit is located on the ground level and operated by one human operator. The robot function can be expanded into diverse ranges of applications such as painting, polishing, plastering, drilling, leaks detection & façade inspection. The robot is currently under pilot testing on the construction site in Hong Kong (O-Matic, 2019).

In spite of R&D efforts over the years, limited robotic applications were successfully launched as commercial products. In general, the global construction robots market is relatively new, yet it is predicted to be one of the fastest-growing markets. The market is divided by the following categories; the degree of automation, operational function, application range, and geographic region. Based on the degree of automation, the robotic building industry comprises of fully automated and semi-autonomous robots, owing to the majority of the current building tasks, so that robots can still function fully automated on-site. Therefore, the semi-autonomous robot accounts for most of the construction robot market share. In terms of the operational function, the construction robot market has divided into façade working robot, masonry work robot, material extrusion robot, e.g. 3D printing robot, concrete work robot, steel fabrication robot, demolition robot, and special purposes robot. The application ranges of the construction robots include residential building, commercial building, and infrastructure. The following section will provide an overview of the selected commercialised construction robots; they mainly focus on the applications that operate on-site, see Figure 13. The author will analyse their function, application, market scope, and the lesson learned from their market approaches.

Commercialised examples:

1. Semi-Automatic Masonry System (SAM): SAM is a semi-autonomous brick-laying robot developed by Construction Robotics from the USA. The conventional method for

building a masonry wall is repetitive, labour intensive, and physically demanding. SAM aims to ease the traditional process by augmenting human labour. The main application for the system is buildings with large, straight elevations. The system uses off-the-shelf parts along with a simple, yet effective positioning, control, and end-effector design to maximise the efficiency of brick masons, improve safety, and to avoid work-related illness or injury. SAM is able to lay more than 3000 bricks a day; the skilled human masons can lay around 1000 a day. The system consists of a mobile platform that travels on the pre-installed scaffold, a material-feeding system that mixes and dispenses mortar, a robotic arm equipped with pick and place end effector, positioning system, power supply, and control system. The positioning system uses a laser sensor to guide the movement of the robot as well as the end-effector. The material-feeding system measures and applies the mortar to the brick. The end-effector on the robot arm will pick and place the brick in the correct position. SAM requires at least two human labourers to carry out finishing work such as cleaning the excess mortar off the brick, ensuring the gaps are correctly filled and sealed, and tidying up the brick joints. The human labour also assists the robot to feed bricks and mortar into the robot while it travels along the scaffold (Construction Robotics, 2019). Armed with the valuable experiences from SAM, the company is continually expanding product ranges and developing new OCR applications.

2. Tybot®: Autonomous rebar-tying robotic system or Tybot® is developed by Advanced Construction Robotics, which is tailored for bridge construction. Rebar tying is extremely repetitive and physically demanding. Especially for bridge deck rebar tying, the work has to be carried out bending over the position as well as while being exposed in the external environments such as rain, wind, and snow. Tybot® will reduce or augment this physical process in bridge construction that improves safety, enhances productivity, and keeps the project on schedule. The system is equipped with a portal crane that covers the current width of the bridge, using the current screed rails as the path at the time so that no extra infrastructure is required. The end-effector is able to identify and tie rebar intersection guided onboard vision system. The quality control technology is implemented in order to perform maintenance and quality checks. The human labour has to position and secure the rebar prior to robotic operation, which counts 10% of the overall operation. The advantages of Tybot® include easy to transport, assembly, highly compatible with the existing construction materials or infrastructures, suitable for varies of applications, and can operate under inclement weather conditions. The system has been pilot tested on-site and is commercially available now (TyBot LLC, 2019).

3. Hadrian X: The Australian company, Fastbrick, developed an autonomous bricklaying robot named Hadrian X. The robotic system can significantly reduce construction time for an average masonry building. It is estimated to building a standard single-story house that will consume approximately 15,000 bricks and take up to six weeks by using the traditional method, while Hadrian can achieve the same result in two days. The system consists of a material feeding system, retractable manipulator, end-effector, Dynamic

Stabilisation Technology (DST™), laser guidance system, control system, and the Fastbrick wall system. The main components of the system can be mounted onto standard bases of trucks, excavators, and boats. The material feeding system is integrated with the retractable manipulator. The key technology for the system is DST™, which assists the end-effector to react on movements caused by wind, vibration and inertia proactively and in real-time. Therefore, along with the laser guidance system the end-effector can achieve remarkable precision. The joint venture company, Wienerberger AG, develops, manufactures, and tests the optimised blocks that are tailored for the robotic end-effector (FBR, 2019). The system is commercially available since 2018.

4. Ceiling drilling robot: The system is developed by the Norwegian company, n-link. The main application of the robot is to provide precise drilling for large commercial, public construction sites ceilings. The system is equipped with a mobile tracked platform, which allows the robot to adapt to most construction site terrains. The elevated work platform, a six DOF robotic arm, vacuum system, and control system are situated on top of the tracked platform. The customized power drill end-effector is guided by a total station and ensures the drilling position is perfectly level. The overall drilling position is acquired through existing construction drawings or BIM data. The system requires at least one operator to control; the control user interface is based on a joystick control along with a tablet-based calibration system. It also contains an on-board power supply system that requires rechargeable batteries. Once fully charged the robot can operate up to one day before recharge. The system is estimated to save up to two days every 1,000 m^2. The system is the first commercialized ceiling drilling robot and the company is aiming to expand the product range in the near future (nlink, 2019).

5. Q-Bot: the UK based company, Q-Bot, developed the underfloor insulation robot. The main function of the robot is to apply insulation material under a suspended timber floor. The traditional method is complicated, time-consuming and disruptive. Usually, the existing floorboard needs to be removed, and then the worker applies insulation in between the floor joist. Q-Bot is equipped with a heavy-duty mobile platform, an on-board camera, power supply, and insulation spray gun. The robot can be folded to access the underside of the floor through the air vent, or through an access hatch from the inside of the property. Once the robot is under the floorboard, the camera will generate a 3D map of the surrounding that helps the robot to identify obstacles, and monitoring temperature or moisture. The control system is easy to operate via a game controller and the operator can navigate the robot guided by the visual input through the on-board camera. The insulation material is accurately applied between the floor joists and continuously monitored and measured in real-time (Q-Bot, 2019). Q-Bot is commercially available and the company is expanding the applications while still working closely with the local authorities to reduce carbon footprints of the UK homes.

6. RAW: Robot at Work from Denmark developed a user-friendly adaptable robotic platform called RAW. RAW is highly customizable, based on the user's requirements

the system can be used for a vast range of construction tasks that include painting, milling, grinding, polishing, cutting, pick & place, and 3D printing. The system consists of a modular supporting and Cartesian travel platform, high payload end-effector support, and a user-friendly control system. The modular frame can be installed on the level elevation of any structure. The system offers a simple Cartesian moment, while the end-effector can be attached on the end of the Z-axis. The user control interface is tablet-based, intuitive, connected by Bluetooth, and the operator does not require any prior programming experience or training to control the operation of the robot (RAW, 2019). The system is commercialized in the meantime the company aims to continuously expand the applications in the near future.

This section showcased six OCRs that have been successfully commercialized. The most compelling findings are the most featured OCRs dedicated to a specific construction task, relatively simple kinematics processes built through off-the-shelf products and long-lasting. Most of the examples demonstrated thoughtful planning in terms of customer segments, value propositions, and business models. For example, Fastbrick is working closely with the brick manufacturer to upgrade the existing market that is beneficial for the robotic application as well as the material supplier. Q-Bot is working with the local building authority in combating retrofitting of the existing housing stocks. Most intriguingly, many of them did not overly complicate the hardware and software integration, and the allocation of functions between human and robot. Additionally, the optimum level of automation is carefully considered throughout the system development stages. Furthermore, the aforementioned companies have involved the customer, and the end-user in the loops of design, development, and testing procedures, so that the finishing product is economical, scalable, and practical.

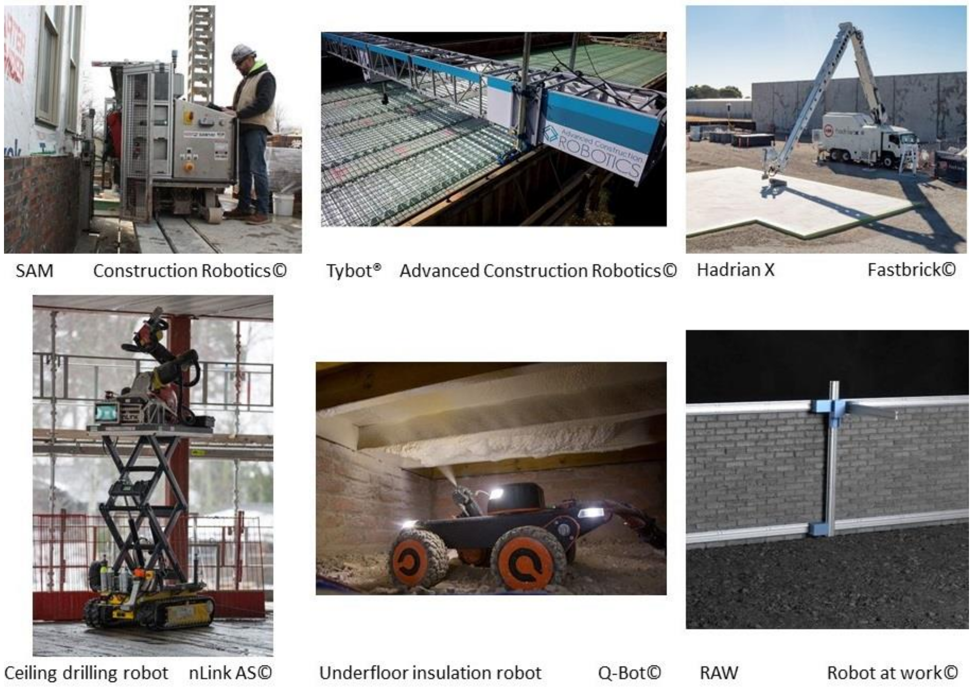


Figure 13: Examples of the OCR that have been successfully commercialized.

2.6 Challenges to implement innovation in the construction industry

Using a new concept in the existing technology to create new market opportunities that links with the existing market is the essence of any innovation. This type of innovation is often referred to as “Niche Creation”; OCR technology also falls into this category. However, there are many barriers in the construction industry that are hindering construction innovation, in particular, the implementation of automation and robotic technologies. In general, the barriers that influence decisions on whether or not to adopt innovation can be summarised as technical, financial, institutional and public (I.A. Motawa, 1999). In this section, the author will investigate the main factors hindering construction innovation.

2.6.1 Innovation in the construction industry

High levels of innovation is the key driver for improving the overall performance of the construction industry. However, the construction industry is less innovative when compared with other industries and this is an international trend. Nevertheless, what could be the reason? To be able to answer this question rigorously, it is important to identify the key factors that influence innovation in construction. The main factors that influence innovation in construction include clients, manufacturers, the structure of production, knowledgebase, hierarchical roles, industry relationships, regulation and policy, and procurement systems. These influences can have a direct impact on decision-makers perspective on innovation and the implementation approach.

Largely, Innovation in construction can be categorised as the following forms, namely, incremental, radical, modular, architectural, and system. The incremental form is used to describe innovation that relies on existing technologies or experiences. The radical form refers to an innovation that is ground-breaking in the scientific domain. The modular form indicates an innovation that improves a part of the larger product, component, or system. The architectural form implies an innovation that has a chain reaction effect on the other component or system. The system form describes an innovation that involves more than one breakthrough and can be integrated with other parts, components, or systems (Blayse and Manley, 2004). In a narrow sense, the innovation in construction can be described as the use of nontrivial change to improve a construction product, process, system, managerial method, marketing, it is original, innovative, and yet bears significant value to the institutional refinement of the construction industry (Slaughter, 1998). Product innovation refers to innovation processes that produce an advanced product that also may result in new product and service creation. On the other hand, it enhances an existing product or service. Process innovation improves either the manufacturing method of a product or improving an existing construction process. Managerial innovation enhances how an organisation or construction project is managed. Marketing innovation aims to adopt an adequate business model to improve customer services as well as increase profitability of the innovation (Arditi, Kale and Tangkar, 1997).

Innovation in construction involves a wide range of stakeholders or participants. As mentioned earlier, they also impose huge influences on innovation activity. The main participants that could take apart of a construction innovation activity include academics, research institutions, manufacturers, contractors, engineers, architects, clients, government authorities, specialists, finance institutions, end-users, public bodies, distributors, service providers, testing facilities, certification bodies, labour, and others. Smooth commutation, mutual understanding and conflicts between so many parties have proved to be a very difficult task in order to form a strong alliance. Therefore, identifying the attributes from the influential factors is extremely useful to pre-access the innovation process, and to evaluate the feasibility, practicality, and economic aspects of the task.

Roles and potential impacts of the main factors, which could either drive or hinder innovation in construction:

- Clients: Clients can influence construction innovation in many ways, and they play one of the most influential roles in terms of driving innovation. Clients can identify unique requirements that have a specific demand in the existing market. Clients' demands can ultimately stimulate a niche market (Seaden and Manseau, 2001). Of course, the competence of the client also determines the influence he imposes on the innovation process. For example, if the client is professional, abstains good understanding of the innovation topic, and has extensive industrial practical experiences, then the client can support the development from an early stage. When clients acquire those qualities, the contribution and collaboration action of the clients will be more innovative and rewarding (Barlow, 2000). Contrariwise, the process will be rather insipid and often resulting in misunderstanding or conflicts.

- Manufacturers: Manufacturers also play a key role in enhancing construction innovation. They offer the knowledge, expertise, and production facility to materialize the design, structure, and integration of an innovative product. They are aware of the market trend and often are in possession of an in-house R&D department (Anderson and Manseau, 1999). Armed with experience, knowledge base, industry networks, they often can upgrade the existing product or market, and establish the upstream and downstream industrial ecosystem for the niche creation.

- Structure of production: It is increasingly accepted that the nature of conventional construction production is hindering the speed of innovation in construction. Innovation can benefit from an ongoing series of transactional knowledge growth. However, the feature of production in construction is often discontinuities, one-off, and dwelling on the traditional method or organisational customs. The nature of the end product, in this case, refers to the building, which tends to be durable and has a longer lifespan than most consumer products (Dubois and Gadde, 2002). The negative consequences are, first, the construction industry prefers the so-called tried and tested approach, and the suppliers and manufacturers have fewer incentives to upgrade the existing product ranges (Pries and Janszen, 1995). In contrast, prefabrication offers a better product model to embrace innovation, due to production volume and diverse product ranges.

- Knowledgebase: Research institutions or universities play a key role in R&D and innovation activities. The construction firms often find it difficult to upgrade their knowledge base between projects and have less motivation or incentive to keep formal in-house research department. This is because the construction industry is comprised of several competencies, loosely coupled, and manipulated by distinctive interests (Gann, 2001). Whereas universities and research institution possess the state of the art information in terms of an innovative concept, deliver rigorous development, and inspire the industry to innovate. However, the research has to focus on the demand from the industry by using applied research techniques.

- Hierarchical roles: The traditional method to manage a construction project also has implications on the innovation speed of construction-related topics (Koskela and Vrijhoef, 2001). The construction process is often subdivided into smaller work packages and project partners, companies that offer professional services will carry out the works (Barlow, 2000). This approach is especially prone to delay or interruption, because of the interdependence relationships between the involved parties. It is imperative to enable to keep the project on track, minimise risks of delay, and to make sure the responsibility is fulfilled. The most common approach is to establish legal contracts that distribute risks and obligations down the project hierarchical structure (Winch, 1998). However, innovation activities will not guarantee the success of a project; especially, during the early R&D stage when there are few tangible benefits that can be used to justify the predefined project performance indicators. This approach has imposed a negative impact on the willingness to innovate due to the risks of breach of contract and resulting in lawsuit cases.

- Industry relationships: The success of construction innovation takes collaboration between related partners rather than rely on a collective of individuals. Hence, industry relationships have a fundamental implication on innovation in construction (Anderson and Manseau, 1999). Construction firms often rely on other organisations, individuals, and firms to materialize innovation. This type of approach lies in inter-organisational cooperation, communication, and interaction that facilitate the translation of knowledge between involved parties (Miozzo and Dewick, 2004). The realisation of the cooperation will determine the success of the design, system integration, information flow, and diffusion of technologies and practices of innovation.

- Regulation and policy: The regulation and policies imposed by the government have a direct influence on innovation speed and attitude towards technological changes. There are two types of regulations. One is called performance-based and the other is prescriptive regulation (Gann and Salter, 2000). The first one is considered more beneficial for innovation activities, in contrast, the second one is more conservative. Regulators are often aware of industry-related knowledge, which helps to shape the overall performance of the industry. Positive innovation outcomes are more likely when relevant regulations and policies are addressed at the early development stage. In addition, the method to measure and reinforce specific regulation or offering incentives can also either drive or hinder innovation in construction (Gann and Ammon, 1998).

- Procurement system: The traditional procurement method discourages the construction industry to adopt non-standard methods, materials, and processes. Very commonly, the traditional approach emphasises project costs, completions speed, distribution of responsibilities, and legal obligations (Kumaraswamy and Dulaimi, 2001). Evidently, the traditional procurement approach, such as lump sum, is counterproductive to innovation (Walker, Hampson and Ashton, 2008). However, there are also some innovative types of procumbent methods that encourage innovation. Especially when the method embraces partnership, joint venture, and consortium within the construction project. In order to enable innovation, the procumbent system needs to shift from competitive tendering to risk sharing and achieving common goals (Bresnen and Marshall, 2000).

The construction innovation process is a complex process that involves many parties and cooperation to commit to a new way of thinking. It is often action-based activities and focuses on how to improve the future performance of the industry. The innovation activities can be described as a translation of knowledge into practice that takes significant efforts, skill sets, and experience from all involved parties (Arditi, 1983). In regards to OCR innovation, this seems more evidential. OCR innovation bears the characteristics of incremental, radical, modular, architectural, and systematic forms of innovation. OCR innovation requires involvement from all stakeholders, cross-disciplinary knowledge base, collaborative industry relationships, encouraging regulations, incentives, innovative procurement system. Yet, in practice to acquire a high level of commitments from all stakeholders, it has been proven difficult. In addition, a commercial OCR system takes up to four years to develop; before on-site testing, there are limited tangible results that will support the predefined system performance indicators. Hence, it requires confidence and commitment, especially from the investor or decision-makers. How to approach them, and how to conduct innovation task strategically, which has significant impacts on OCR development, are key concerns.

2.6.2 Fragmentation of the construction industry

In general, there are two types of fragmentation in the construction industry, internal fragmentation and external fragmentation. The internal fragmentation implies issues, or miscommunication between project partners, especially project partners that shares a common interest. The external fragmentation refers to the involvement of non-alliance organizations such as government authorities and policymakers in various stages of the construction project (Abadi, 2005). The construction industry has a very complex structure, which involves a multitude of stakeholders. Each stakeholder carries specific areas of interests, expertise, governed by different institutional rules and regulations. The construction project consists of multiple processes and each task is performed by a specialist under a strict hierarchical role that is reinforced by contracts. The complexities of the construction project are often associated with project resources, site condition, design, skill sets, and other types of unpredictable elements, such as environment and economic situation. Some researchers believe that fragmentation in the construction industry is directly inherited from the traditional procurement strategy (Dainty, Briscoe and Millett, 2001). However, standard building design, construction techniques and managerial style have defined professional segmentation and the segregation of positions and duties in the construction project. These characteristics will increase uncertainties, interdependencies between project partners, and ultimately increase the risks of rework, delay, and overspending (Anumba, Baugh and Khalfan, 2002). The main impact of fragmentation in the construction industry can be reflected in the following aspects.

Lack of communication: Due to the complexity of the construction project, inadequate communication has been reflected throughout the entire project phase. During the design stage, the information flow between the architects, engineers, and local authorities is mandatory (Mohamad, 1999). However, the process can be very time consuming, which is partially due to hierarchically distributed roles and responsibilities, as well as unacquainted with each other's professional area. The interaction between contractor, sub-contractor, and the rest of the parties during the design stage has been reported to be very limited. In order to achieve the project expectations, it is essential to establish systematic coordination and communication to ensure cross-disciplinary interaction between all project partners.

Lack of centralised focus: First, the traditional type of construction project is focused on an individual project, a project team will be established on a temporary basis. In terms of the project team, it is loosely coupled, which results in decentralised decision-making. Because the project participants are separate individual, there is a lack of centralised management, coordination, and procumbent process. Second, many clients will not be fully involved in the duration of the project. The client hypothesizes that once the design is approved, the construction process should meet all expectations. This is because the client is not aware of the design and the separate construction process, both of which are influenced by completely different sets of rules and regulations (Baiden, Price and Dainty, 2006).

Adversarial mentality: As mentioned earlier, the construction industry is predominantly based on one-off projects and temporary collaboration. The issues of fragmentation are embedded in the project relationships as well as construction processes. There is an apparent diversity of priorities among the architects, engineers, contractors, and local authorities. For example, the architects hope the building reflects the design concept in terms of aesthetics and special proportion. The engineers focus more on the constructability aspects of the building and try to mitigate delay and safety hazards. The local authorities are interested in whether the project complies with planning, building regulations, and addresses local demand. This type of loosely coupled relationship is prone to conflicts and misunderstanding between the involved project parties (Hegazy, Zaneldin and Grierson, 2001).

The standard building industry is generally fragmented, loosely coupled, lacking customer focus and inefficient in many respects. It is even more challenging when adopting OCR technologies. This is because OCR potentially requires involvement from industries sectors that have never collaborated with the construction industry. Thus, the issues of fragmentation can be intensified if the R&D, implementation, and market adoption activities are not structured and approached strategically.

2.6.3 Market acceptance

The previous section has described the challenges of adopting innovation in construction. In this section, the author will explore the nature of the OCR, define the product terminology, market chronology, the elements necessary to take into consideration from the product development phase, and prior market adoption phases to ensure the innovative product will emerge with the construction industry successfully.

Introducing OCR in the construction industry requires extensive diffusion of innovation. OCR market consists of the utilisation of cross-disciplinary knowledge transfer and collaboration of multiple industries. As mentioned earlier, the OCR technology can be classified as a niche creation, which is used as a new concept within the existing technology to create niche market opportunities that link with the existing market. The main players engaged in the growth of OCR, however, are the current automation and robotics, and the building industries are clearly inconsistent with OCR. Both sectors present a distinctive edge in the field, yet demonstrate noticeable limitations in understanding each other's professional domain. For example, conventional automation and robotic firms focus on the technology applied in the mainstream manufacturing sectors. They do not possess or have very limited knowledge about construction. In contrast, the construction sector, especially in the on-site construction field, very few attempts to implement automation and robotics were ever made. Thus, even though OCR relies on such technologies, like hardware or software from the existing automation and robotic sector, nevertheless the development of OCR also requires a knowledge base from the construction industry, and the result of the technology integration between these two domains can be treated as radically new technologies.

As a radically new technology, OCR can either remain as a niche creation that continuingly offers new market opportunities or featured to the emergence of a mass market. This depends on the technology transition path, marketing strategies, and the stakeholder's interests prior to, and after product launch (Ortt, Langley and Pals, 2015). The detailed analysis in regards to OCR technology adoption, market adaptation, institutional adoptions in management, organization, learning, and training will be demonstrated based on the case study in the later section. The main barriers and, external factors that would influence the OCR market adoption phase are summarized as below.

- Lacking knowledge of the technology: When the technology is new to a customer, technology provider, end-users, and regulators this will impose difficulties in identifying requirements, KPIs, customer segments, development strategies, demonstration methods, and establishing institutional measures (Ştefan, 2015).
- Technology visibility & Cost-benefits: Because OCR is radically new in the market, the functionality, performance ratio, investment costs, and direct cost-benefits or incremental benefits are yet to be determined. There are minimum references that can be used to compare OCR with the existing market. Therefore, the construction industry as a whole is less motivated to explore new technologies unless there are indispensable demands.

- Lacking infrastructures that facilitate OCR: There is a very limited infrastructure that supports OCR development, testing, operation, service, training, marketing, and certification. Due to the market size, it is still emerging and has not yet reached the mass market. Moreover, there is limited incremental positive incentive to stimulate infrastructure development (Ştefan, 2015).
- Government initiatives: A clear target, vision, incentive plan, or providing research recourses are instrumental in stimulating OCR development and market adaptation. Industry-government collaboration also has huge implications on the successes of OCR development.

OCR relies on a different type of market-based structures, which requires different approaches in terms of technical, political and institutional substances. Thus, various types of market readiness levels need to be investigated in order to measure the maturity of the product. The main categories of market readiness levels are briefly introduced as follow.

- Technical readiness level: The National Aeronautics and Space Administration (NASA) developed TRL that is used as a systematic metric or measurement system to assist monitoring technology development (Mankins, 1995), see Table 14. OCR should adopt a similar concept to evaluate the product development activities and to assist the decision-makers in understanding the technologies, managing development tasks, reduce risks, securing research funding, and transitioning of technologies (Sadin, Povinelli and Rosen, 1989).
- Integration readiness level: Due to the nature of OCR, the product requires extensive integration of systems. Only TRL is not sufficient, because TRL does not offer the status of the entire system integration phase. Integration readiness level (IRLa) can be used to measure the interaction, compatibility, reliability, and performance between technologies, to evaluate potential risks, and enhance integration between individual system and other technologies, see Table 15.
- System readiness level: The system readiness level (SRL) is used to define the current state of development of a system, see Table 16. SRL incorporates individual TRLs along with consideration of IRL1. SRL measures the entire system development life cycle, by verifying and validating the relationships between TRL and IRL1 in both component level as well as system integration level (Sauser *et al.*, 2006). Considering OCR, SRL is particularly important during the design and system implementation stage.
- Innovation readiness level: The innovation readiness level (IRL) is designed to assist the project management team to evaluate the innovation process and take into accounts of the related key elements, see Table 17. The related key elements include technology, market, organisation, partnership, and risk. Technology refers to hardware, software applications, manufacturing, operation, training, services, and maintenance aspects of innovation activities. Market expresses the identified customer segments, and which of those companies, organisations, and individuals are interested in the innovation. Organisation maturity determines the capability of a firm to deliver service, product, and innovation. The partnership contains all the stakeholders that engaged in an

innovation activity. Risk refers to the assessment of potential negative impacts on various phases of innovation activities.

- Demand readiness Level: The demand readiness level is another scale of the traditional TRL. It is based on the essence of the market pull strategy, which is used to measure the maturity of evolving demands, to evaluate the market acceptance of the conceptual ideas that assist research team to decide if it is the right time to push the scientific research into practical application (Paun, 2011), see Table 18.
- Manufacturing readiness level: The manufacturing readiness level (MRL) defines the critical risk lays in immature product technology and manufacturing capability during the technology transition period, see Table 19. Manufacturing readiness and technology readiness is closely associated, MRL will be more mature once TRLs and product are well defined (Fernandez, 2010). In the case of OCR, the MRL is a crucial tool to measure the manufacturer's capability to produce prototypes or the final product in production relevant environment, production representative environment, and pilot line environment (Fernandez, 2010).
- Policy readiness level: The policy readiness level (PRL) is a tool that is designed to analyse what types of policy or initiatives the policymaker should be considering to adopt that encourages policy coherence, strengthening the existing policy and proposing changes in support of a specific innovation. Currently, there is a very limited policy instrument or mechanism that is focused on OCR related topics (Nykiforuk *et al.*, 2011).
- Institutional and legal readiness level: The institutional and legal readiness level is still a conceptual term. There are very few attempts to use it for measuring social acceptance or societal implication on technology transition. In terms of OCR, the readiness concept will provide guidance to researchers, funding institutions, and other stakeholders in the value-chain to validate what legislations and laws are in place or lacking that can drive or hinder the research progress (Aasrud, Baron and Karousakis, 2010).

Table 14: Technology Readiness Levels, according to (Mankins, 1995).

Technology Readiness Levels (TRL)	
TRL 1	Basic principles observed and reported
TRL 2	Technology concept and/or application formulated
TRL 3	Analytical and experimental critical function and/or characteristic proof-of-concept
TRL 4	Component and/or breadboard validation in a laboratory environment
TRL 5	Component and/or breadboard validation in a relevant environment
TRL 6	System/subsystem model or prototype demonstration in a relevant environment
TRL 7	System prototype demonstration in a space environment
TRL 8	Actual system completed and "flight qualified" through test and demonstration
TRL 9	Actual system "flight-proven" through successful mission operations

Table 15: Integration Readiness Levels, according to (Sauser *et al.*, 2006).

Integration Readiness Levels (IRLa)	
IRLa 1	An interface (i.e. physical connection) between technologies has been identified with sufficient detail to allow characterization of the relationship
IRLa 2	There is some level of specificity to characterize the interaction (i.e. ability to influence) between technologies through their interface

IRLa 3	There is compatibility (i.e. common language) between technologies to orderly and efficiently integrate and interact
IRLa 4	There is sufficient detail in the quality and assurance of the integration between technologies
IRLa 5	There is sufficient control between technologies necessary to establish, manage, and terminate the integration
IRLa 6	The integrating technologies can accept, translate, and structure information for its intended application
IRLa 7	The integration of technologies has been verified and validated with sufficient detail to be actionable

Table 16: System Readiness Levels, according to (Sauser *et al.*, 2006).

System Readiness Levels (SRL)	
SRL 1	Refine the initial concept. Develop system/technology development strategy
SRL 2	Reduce technology risks and determine an appropriate set of technologies to integrate into a full system
SRL 3	Develop a system or increment of capability; reduce integration and manufacturing risk; ensure operational supportability; reduce logistics footprint; implement human systems integration; design for producibility; ensure affordability and protection of critical program information; and demonstrate system integration, interoperability, safety, and utility
SRL 4	Achieve operational capability that satisfies mission needs
SRL 5	Execute a support program that meets operational support performance requirements and sustains the system in the most cost-effective manner over its total life cycle

Table 17: The framework of Innovation Readiness Levels (IRL), according to (Lee, To Chang and Chang Chien, 2011).

The framework of Innovation Readiness Levels (IRL)					
IRL	**Technology**	**Market**	**Organization**	**Partnership**	**Risk**
IRL 1 (Concept)	Basic principles observed and reported	Working closely with the key customer; to gain customer demand; observe for radical innovation; allocation of initial market	Strategy confirmed; informal, loose structure amongst R&D team established	Potential partners identified	Technical, integration risk considered
IRL 2 (Components)	Individual components tested; prototypes demonstrated; IP protected	End-user identified; detailed market launch strategy issued	Business analysed and plan issued; key players involved	Key partners selected; calibration established; customer involvement	Technical, integration risk assessed; organization risk considered
IRL 3 (Completion)	Launch expertise formed; technology/ product documented	Defined requirements of the customer; market segment, size, and share predicted; pricing issued;	Establish a core management team; customer value creation; establish a collaboration platform	The partnership formally established; supply chain established	organization risk assessed

		information management			
IRL 4 (Gap)	General availability to the market; establish after-sales supports; design and facilitate continuous innovation	The business model established; competitors identified	Inter-organizational innovation; cooperation inside the value chain	Cooperation with dynamic network	Organizational risk periodically assessed
IRL 5 (Competition)	R&D activities; technology maintenance enabled; technological service provided	Provide service and solutions; business mode refined; market strategy	Enhanced effectiveness and cooperation; organizational learning	On-going management	Organizational risk periodically assessed
IRL 6 (Changeover/ termination)	Disruptive innovation identified; lesson learned; re-innovate or exist	Declining market confirmed; market research for approval to re-innovate or exist		Partnership terminated	Changeover, or terminate

Table 18: Demand Readiness Levels, according to (Paun, 2011).

Demand Readiness Levels (DRL)	
DRL 1	The occurrence of a Feeling “something is missing”
DRL 2	Identification of a specific need
DRL 3	Identification of the expected functionalities for the new Product/Service
DRL 4	Quantification of the expected functionalities
DRL 5	Identification of the systemic capabilities
DRL 6	Translation of the expected functionalities into needed capabilities to build the response
DRL 7	Definition of the necessary and sufficient competencies and resources
DRL 8	Identification of the Experts possessing the competencies
DRL 9	Building the adapted answer to the expressed need on the market

Table 19: Manufacturing Readiness Levels, according to (OSD Manufacturing Technology Program, 2010).

Manufacturing Readiness Levels (MRL)	
MRL 1	Basic manufacturing implications identified
MRL 2	Manufacturing concepts identified
MRL 3	Manufacturing proof-of-concept developed
MRL 4	Capability to produce the technology in a laboratory environment
MRL 5	Capability to produce prototype components in a production relevant environment
MRL 6	Capability to produce a prototype system or subsystem in a production relevant environment
MRL 7	Capability to produce systems, subsystems, or components in a production representative environment
MRL 8	Pilot line capability demonstrated; ready to begin low rate initial production

MRL 9	Low rate production demonstrated; capability in place to begin full-rate production
MRL 10	Full rate production demonstrated and lean production practices in place

2.6.4 Cross-disciplinary collaboration and training

The construction industry has been described as highly fragmented, with apparent market segregation, and lacking partnership and collaboration between supply chains. When attempting to introduce OCR, it is key to pay attention to multi-disciplinary collaboration and communication, because the stakeholders across the value chain are not familiar with the technology. The roots of these issues are deeply embedded in every step of the R&D phase. In fact, this trend is triggered at the beginning as soon as a student enters the higher, or vocational education system.

Due to the current market-oriented research focus and specific education curriculum, universities pay more attention to market-driven professional training; in contrast, they pay less attention to interdisciplinary teaching. Students often know very little about subjects outside their academic domain. For example, students who are studying architecture and civil engineering rarely have any knowledge of automation and mechanical design. However, in order to conduct research and development of construction robots, they must be proficient in traditional construction method design, building structure, engineering management and other disciplines, and understand the auxiliary knowledge about microelectronics, big data, artificial intelligence, mechanical design and manufacturing and automation, so interdisciplinary teaching and cooperation in the field of construction robotics is essential. There is a positive example concerning cross-disciplinary teaching, a collaboration that the author would like to demonstrate.

The Chair for Building Realization and Robotics at TUM launched the Master course Advanced Construction and Building Technology (ACBT) in 2011. The ACBT course aims to expand the knowledge base of the traditional sense of architecture, construction engineering, and construction management by combining competencies in the field of automation and robotics, mechatronics, innovation management, and Information and Communications Technology (ICT). In ACBT, candidates have opportunities to receive the state of the art knowledge from the various academic field. The course was taught in English to attract international applicants, and the instruction methods include lectures, workshops, seminars, site visits, and guided team works. The course modules were designed in a way that is self-explanatory and well structured so that even students without previous experience are still able to follow. The course attracted candidates from eight distinct academic and professional backgrounds, including architecture, industrial engineering, electrical engineering, civil engineering, enterprise, interior design, computer science and mechanical engineering. Fortuitously, the author was admitted to the first generation ACBT study and successfully graduated from the course. The author considers the course as beneficial for students from various educational backgrounds to gain the basic knowledge of construction automation and to acquire the first-hand experience to carry out multi-disciplinary collaboration and communication systematically.

2.7 Summary

This chapter provides primary research that offers several aspects to justify research motivation, direction, and intention. First, to provide an overview that explains the current situation of the Hong Kong construction sector, in particular, the Hong Kong PHC sector. The author identified the immediate challenges faced by those sectors. For instance, increasing construction costs, land shortage, skilled labour shortage, health and safety, and institutional conditions. In order to gain an understanding of the PHC sector, the author has provided detailed explanations in terms of the history, construction methods, and the recent technological breakthroughs, and the efforts made in the PHC development. Based on the research, the author considers that automation and robotics can potentially offer an alternative solution to solve some of the aforementioned challenges. Yet, there are profound implications when introducing new technology into the traditional construction industry. Second, a holistic approach was used to demonstrate the feature and the difference between the industrial robot and construction robot, and to analyse the reason and method of how to adopt automation in the other sectors. However, the construction sector is fundamentally different from the manufacturing industry and it seems difficult to directly copy the automation technology adoption method from the manufacturing industry and to expect it will work in the construction industry. Nevertheless, studying the cross-disciplinary approaches can provide valuable insights into the construction industry. Third, an extensive overview of the existing and state of the art construction robotic and automation technologies was illustrated. By doing so, the author evaluated the system features and functions of the selected applications. Consequently, the lessons learned from those commercialized OCR applications were summarised. Last but not least, the author evaluated the aspects that can hinder or drive innovation adaptation, especially when implementing OCR in the construction sector.

The earlier section represents the desperate demand from the PHC sector in Hong Kong, but many modifications need to be considered when implementing OCR technology in the traditional construction industry. It is important to avoid radical changes for the well-established yet conservative industry, such as the construction industry. A progressive strategical approach is required and to be distributed in each stage of the development process. It is crucial to make the stakeholders aware of the proposed technology. It is also crucial to involve the client and end-user from the beginning of the R&D process. The researcher needs to take into consideration the existing construction methods, on-site condition and other unique characteristics, which have implications to the decision making. Namely, these include assisting the decision-makers to set clear goals, objectives, and strategies in terms of design, testing, implementation, marketing, and policymaking. A strong project partnership from an early stage is highly recommended to prompt systematic coordination and communication to ensure cross-disciplinary interaction between all project partners.

3 Methodical development based on the Hong Kong case study

The previous chapter reviewed the innovative construction automation technologies to date, relating to the current situation of the Hong Kong PHC sector and identified the constraints that the industry may experience when implementing automation and robotic technologies in the conventional construction industry. In this chapter, based on the case study, a comprehensive investigation into the stakeholder, requirements, the existing PHC construction method, and the on-site condition is carried out. A systematic method is introduced that can serve as a guideline on how to identify key stakeholders, to verify design requirements, to identify and define how to automate a specific construction task. In addition, it can demonstrate how to develop a COR that is scalable and adaptable to the changes in market demands. The marketing strategy will be described in chapter 4.

3.1 Project background

The CIC consultancy project on investigating the potential of implementing robotics and automation in the context of large-scale housing development for Hong Kong was initiated in late 2017. The project is solely financed by the CIC. The CIC is a statutory body that detects the demands from the construction industry and is working closely with industry practitioners, contractors, academics, and government authorities, aiming to bridge the gaps between government and the Hong Kong contractors. In chapter 1, the author demonstrated results from the initial research. The biggest challenge the Hong Kong construction industry faces are summarised as labour shortage, demographic change, diminishing speed, increasing housing demand, increased construction cost, inconsistent quality, and safety. During the initial research process, the author also investigated the existing construction methods, in particular, the methods used in the PHC sector, and evaluated if automation and robotic technology can offer an alternative in solving the aforementioned issues.

However, as described in chapter 2 the modern buildings consist of many complex structures, layouts, and subsystems. In addition, the construction industry is fragmented and can be influenced by other attributes, for example, market demand, economy, technology, skill sets, and institutional policies, resulting in imposing huge constraints when applying robotic technologies in construction. Hence, in the early development phase, it is vital to be aware of key stakeholders' requirements, understand the existing construction operation, setting realistic goals, define priority areas and analytically evaluate the development activities. The step-by-step strategical approach of how to execute these tasks will be presented inline along with the outcomes of the case study. Essentially, the systematic approach serves as the backbone of the comprehensive guideline.

As mentioned in chapter 1, the project has been divided into four phases, see Figure 14. At the time of this writing, the first phase of the project has been successfully completed. The case study referring to the completed tasks belong to the phase one project. Phase two, three, and four will be briefly discussed in order to offer a complete project flow, but they are not the focus. Some tasks have been conducted in between phase one and two, for example, the CBA, critical proof of concept of system design and integration concept. These activities will be demonstrated in later sections.

Phase one consists of seven stages that include stage one initial research and literature review. Stage two is focused on an online survey. Stage three is related to the on-site case study. Stage four comprises the co-creation workshop. Stage five describes concept development and initial design. Stage six documents mock-up construction and demonstration, and stage seven discuss roadmap building, see Figure 15. In general, stage one through stage four concentrate on the identification of research priority areas, requirements, and system selection.

These four stages provide the principal strategies in relation to the activities that need to be carried out prior to the initial design and development stages. The objectives of stage one are to introduce the project scope, goals, and predicted outcomes to the client; to identify key stakeholders; to conduct an initial study of the current situation; to define the preliminary development scopes. Stage two will focus on the on-line survey, as well as establish the groundwork that occurs prior to distributing the survey. Stage three is to conduct an on-site case study. The purpose of this stage is to acquire first-hand feedback from the on-site labour, project manager, and contractors. Defining realistic criteria to determine specific demands allows the developer to explain the course of research and narrow down the focus on development. Stage four consists of co-creation workshops that utilise the results and feedback from the previous stages to define priority areas; to confirm research direction and further narrow down the development focus. Each stage will generate a separate set of results, and thorough analysis of the common aspects and variations in particular feedback, this approach can stimulate the project team in deciding a concrete direction for the system development, see Figure 16.

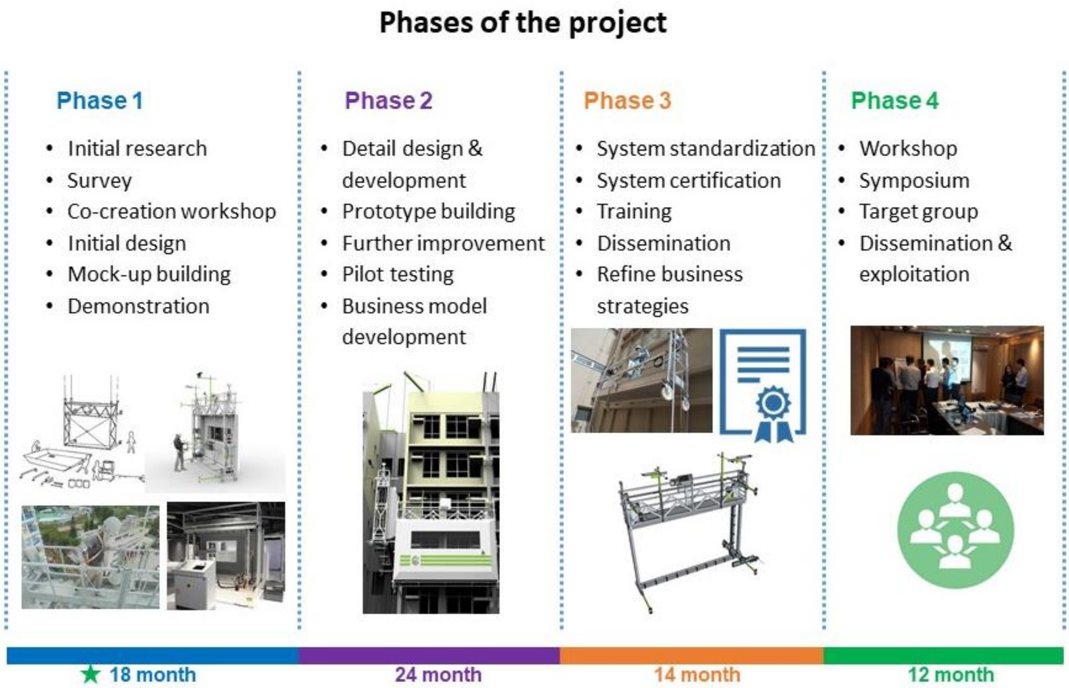


Figure 14: The phases of the project, at the time of this writing, the first phase of the project has been successfully completed.

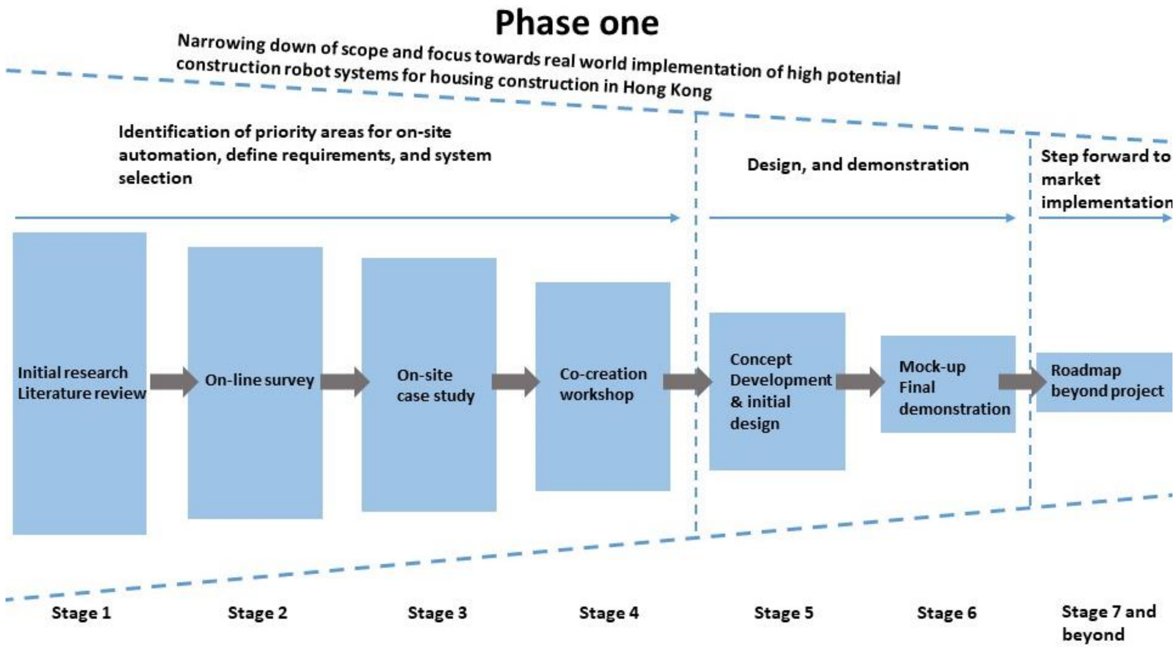


Figure 15: Various stages that belong to the phase one project.

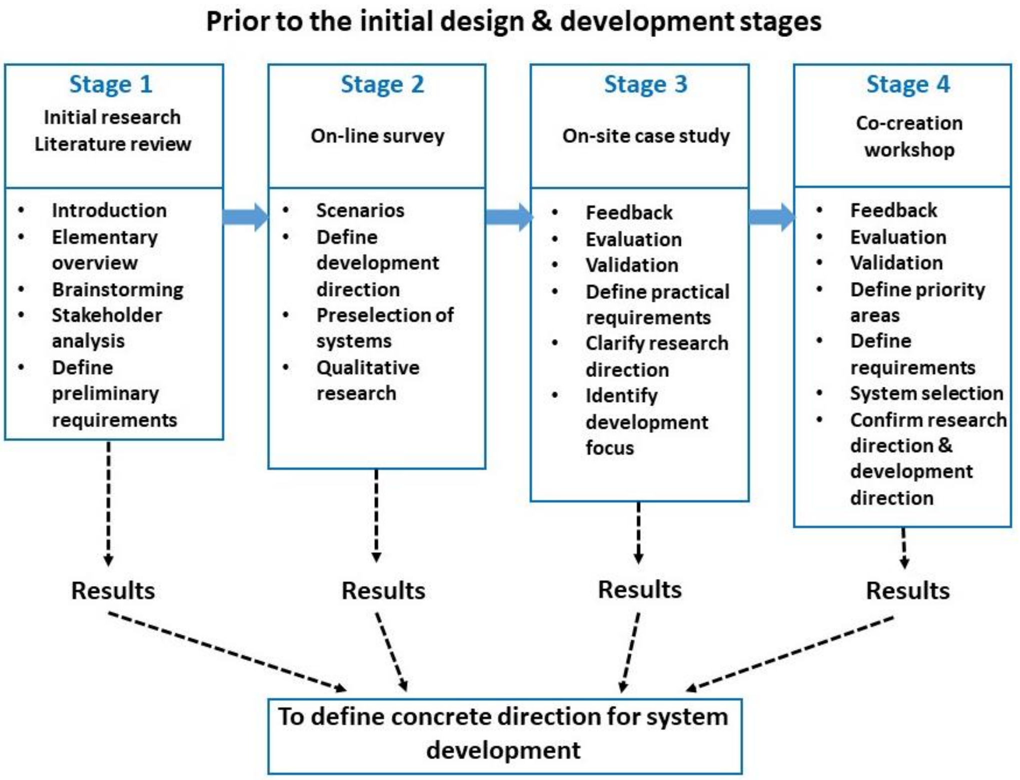


Figure 16: A brief description of the first four stages within the phase one project.

3.2 Stakeholder analysis and initial requirement identification

Identifying the key stakeholders is an important task, wherein usually, the first step is to establish the relationships between project participants and has a huge implication on the success of a project. Stakeholders can be individuals, groups of people, companies, and institutions. They may be directly involved in a project, or partly contribute to a project; they could impose as either driver or barrier to a project, or they could be affected by the outcome of a project. In this case, due to the complexity of the construction industry, stakeholder analysis becomes a consequential part of the consultancy project. It is particularly important to help the project leader identify the relationships between the involved parties and the project. Many stakeholders possess multiple stakes in the business, which belong to more than one stakeholder group. Therefore, it is important that their goals and priorities are not divided or viewed as independent parties. In addition, during the different project phases, the levels of the involvement and interests of the stakeholders may vary (Freeman and David, 1983).

Because of the CIC project consist of varies of phases, the motive and interests of the key stakeholders may change over time. Sometimes, the changes of interest or relationship will be caused by the outcomes of the specific phase of the project. Therefore, stakeholder analysis is an iterative process, which should be repeated at each phase of the project to evaluate their interests, relationships, and interactions. When the focus of the project changes from one phase to another, the key stakeholder's objectives and interests will be addressed accordingly. The following section will briefly introduce the purpose of stakeholder analysis, the categories of varies of stakeholders, and the use of the CIC project as an example to demonstrate how to conduct stakeholder analysis in practice.

The main objectives of a stakeholder analysis include:

- To identify the key stakeholders in regards to the project
- To explore the interests, objective, and impact of the stakeholders
- To explore the multiple and interdependent interactions between stakeholders
- To identify what type of resources the stakeholders are likely to contribute
- To identify conflicts of interests between stakeholders
- To analyse the capacity and knowledge base of different stakeholder groups
- To identify communication methods between each stakeholder
- To develop an appropriate stakeholder management system

In a broad sense, stakeholders can be categorised into two groups, which are:

- Primary stakeholders: These stakeholders have a long-term relationship that is interdependent with the firm, and will suffer the most when the firm declines or is faced with issues, and share the most interests or risks as a result of the firm's operation (Freeman and David, 1983).
- Secondary stakeholders: These stakeholders are indirectly affected by the operation of the firm. They have a significant influence on a decision, yet are not directly involved

with the operation, and legal, economic, and institutional constituents do not directly affect their interests.

When based on a risk-based model, the stakeholders can be divided into two classes: voluntary and involuntary stakeholders. Some of the voluntary or involuntary stakeholder classes also belong to either primary or secondary stakeholder groups (Clarkson, 1994). The two classes are:

- Voluntary stakeholders: The parties who are knowingly involved with a firm's operation, and have the capacity to decide to either enter or withdraw from a relationship whenever possible.
- Involuntary stakeholders: The parties who are unknowingly affected by the firm's operation, and do not have the jurisdiction to choose either to enter or withdraw from a relationship.

There are two varieties of stakeholder elements, which are associated with the aforementioned stakeholder group, but sometimes it is difficult to decide the involvements of stakeholders that share more than one stakes or interests throughout the firm's value chain. The elements are:

- Internal: The internal stakeholders often refer to the parties that are closely associated with the firm, and whose decision can directly influence the development outcome of the project.
- External: the external stakeholders are those who are not directly associated with the firm.

3.2.1 Method

In the CIC project, in relation to stakeholder analysis, the objectives of the task are to identify the categories of key stakeholder groups, to evaluate classification, disaggregation, disposition, impacts between the key stakeholders, and initial requirement identification. The first step is to develop a list of stakeholders and to them according to their need, interests, and contribution during the first phase of the project. Contributions toward the task come from the project team from CIC, TUM, Hong Kong research institutes, and the construction practitioners as informers. Based on the experiences and backgrounds of the informers, a group of stakeholders are identified, which covers the public sector, private sector, and the societal level. The second step is to disaggregate the selected stakeholders to define their specific interests, demands and potential impacts on the projects. This method can help the project leader define the initial hierarchical order of the key stakeholders. The third step is to establish a "Power-interest Grid" system that allocates stakeholders into different grid groups based on their interest and power. This method also helps the project leader to dispose of the key stakeholders into specific groups that potentially shift between more than one grid positions (Mitchell, Agle and Wood, 1997). The fourth step is to evaluate and estimate the impacts of each stakeholder in different project phases to gain a better understanding of the transformation of power or interest across the grid. By doing so, the project leader can strategically assign time and resources to support those stakeholders that are in the low power/high-interest quadrant and to encourage them to move into the high power/high-interest quadrant to remove or reduce efforts on stakeholders that are in low power/low-interest quadrant. In addition, this is done to seek strategies to increase the interest level of those stakeholders who belong to the high power/low-interest quadrant (Ackermann and Eden, 2011). The fifth step is initial requirement identification that will select functional and non-functional requirements based on the stakeholder analysis. The following section demonstrates the specified steps in detail.

Stakeholder identification:

Table 20 illustrates the identified stakeholders within project phase one that has been divided into public, private and societal sectors.

Table 20: Stakeholders sectors and levels.

Project phase	**Stakeholder sectors/levels**		
One	**Public**	**Private**	**Societal**
	CIC	Contractors	Society & community
	Research institutes	Service providers	Environment
	Government agencies	Sub-contractors	
	Regulatory organisations	Integrators	
		Manufacturers	
		Suppliers	
		Labour	
		Architects	
		Engineers	
		Competitors	
		Public housing tenant	

Table 21 illustrates the classification of the stakeholders under three pre-identified sectors. In general, the classification divides the stakeholders into two groups (primary and secondary), two classes (voluntary and involuntary) and finally, two elements (internal and external).

Table 21: Stakeholder classification.

Project phase one			
Stakeholder / Public sector	**Primary / Secondary**	**Voluntary / Involuntary**	**Internal / External**
CIC	Primary	Voluntary	Internal
Research institutes	Primary	Voluntary	Internal
Government agencies	Secondary	Voluntary	External
Regulatory organisations	Secondary	Voluntary	External
Stakeholder / Private sector			
Contractors	Primary	Voluntary	Internal
Service providers	Primary / Secondary	Voluntary	Internal / External
Sub-contractors	Primary / Secondary	Voluntary	Internal / External
Integrators	Primary	Voluntary	Internal
Manufacturers	Secondary	Voluntary	External
Suppliers	Secondary	Voluntary	External
Labour	Primary / Secondary	Voluntary	Internal / External
Architects	Secondary	Voluntary	External
Engineers	Secondary	Voluntary	External
Competitors	Secondary	Voluntary	External
Public housing tenant	Secondary	Voluntary	External
Stakeholder / Societal level			
Society & community	Secondary	Involuntary	External
Environment	Secondary	Involuntary	External

Disaggregation and uniqueness of the stakeholders:

Table 22 below specifically pinpoints the stakeholders that belong to each group, based on the context of the CIC project.

Table 22: Disaggregation and uniqueness of the stakeholders.

Stakeholder / Public sector	
CIC	Committee on Productivity Hong Kong Institute of Construction (HKIC)
Research institute	Universities and research institutes e.g. TUM, HKUST, HKSTP, RCC, and Hong Kong R&D Centre for Logistics and Supply Chain Management (LSCM).
Government agencies	HKHA, HKCA, CIG, BD, HKCTU, Hong Kong Housing Society (HKHS), Hong Kong Federation of Trade Unions (HKFTU), Environmental Protection Department (EPD), Town Planning Board, Government Property Agency (GPA), Employees Retraining Board (ERB), Vocational Training Council (VTC), Hong Kong Institute of Construction (HKIC), Hong Kong Automation Technology Council (HKATC).
Regulatory organisations	Non-Destructive Testing (NDT), Electrical and Mechanical Services Department (EMSD), Building Environmental Assessment Method (BEAM), Product conformity certification schemes (PCCS), Hong Kong Service Suppliers (HKSS), Hong Kong Institute of Construction (HKIC), CIC.
Stakeholder / Private sector	
Contractors	All approved contractors for public works, in particular, the specified "Group C" that for contracts of value exceeding HK$ 300 million (Development Bureau, 2019).
Service providers	Firms that offer a specific service, solution to the end-users, for example, maintenance, repair. However, in the case of the CIC project and the context of OCR, such service provider is not available.
Sub-contractors	Firms that provide specialist services, especially related to the construction trade. For example, external wall painting, tiling, excavation, metal fabricator, concreter, plumber, and others.
Integrators	Firms that are familiar with automation and robotics, application development, mechanical engineering, system optimisation and integration.
Manufacturers	Firms that possess expertise in manufacturing of industrial products, in particular, robotic systems.
Suppliers	Firms that provide parts, components, services, software, hardware applications related to automation, robotics, construction, equipment, and machinery.
Labour	The general labour, skilled labour, site personnel, or anyone that is involved in the construction process, e.g. deliver driver from a logistic sub-contractor
Architects	Architectural Services Department (ASD), and individual architectural services companies.
Engineers	Civil Engineering and Development Department (CEDD), and individual engineering firms.
Competitors	Companies, organisations, and individuals that are doing or planning to carry out similar business activities or product.
Public housing tenant	The current or prospective public housing tenant.
Stakeholder / Societal level	
Society & community	People or social elements that are knowingly or unknowingly affected by the operation. Some of them are not quantifiable or tangible. For instance, public acceptance of innovation or incremental influences due to changes in legislation.
Environment	Environmental Protection Department (EPD) or environment-related issues that could trigger social instability.

Table 23 describes the distinct interest, demand, and impacts of the identified stakeholder groups. This exercise will be extremely important to assist the designer in understanding each individual stakeholder's interests, demands, and to avoid conflict of interest while developing the system.

Table 23: Stakeholders interests, demands, and impacts.

Stakeholder / Public sector	
	Interests, demands and impacts
CIC	Interest: To convey the industry's demand and to improve the overall performance of the conventional construction industry in Hong Kong. Demand: More innovative approach, long-term strategies that will enhance the construction industry as a whole. Impact: Key player in terms of leading and promoting industry upgrade, stimulating ground-breaking insight on innovations, and influences government initiatives or motivations.
Research institute	Interest: To conduct research and propose innovative strategies that are practical for solving the issues in the industry. To promote research excellence and to explore the research results. Demand: Sufficient funding, incentives, transparency in technology and interdisciplinary collaboration. Impact: Promote innovation in construction, provide state-of-the-art solutions, and encourage interdisciplinary approach.
Government agencies	Interest: To maintain prosperous development in its own domain, while positively influencing the construction industry. Demand: Strategies that can bring a positive impact to the official demands. Impact: Can potentially influence the institutional, political aspects of the industry and could either drive or hinder the operation relates to the project.
Regulatory organisations	Interest: Regulating certifications, to publish new regulations or amend the existing ones, and impose prospective changes in the system. Demand: Advice, or strategies that can enhance the existing operations. An action plan that covers an area that is not yet measured by any regulation. Impact: To cover the areas that are not yet regulated or proposing new regulations and certification systems to an emerging market or product.
Stakeholder / Private sector	
Contractors	Interest: To improve the existing construction operation, increase productivity, reduce time, cost, and improve the health and safety aspects of on-site tasks. Demand: Cost-effective, practical, and innovative strategies that can address one or more issues faced by the industry. Incentives from the government. Transparency in technology and interdisciplinary collaboration. A well-established infrastructure that is supporting the emerging market. New upstream and downstream industrial ecosystem. Impact: To promote innovation in the construction industry. To identify the functional and non-functional requirements that can significantly influence the development direction of the project.
Service providers	Interest: To expand the existing services, to provide new services for an emerging market. Demand: A well-established infrastructure that is supporting the emerging market, and enhances the existing business. Impact: To generate new business markets, and upgrade the existing market.
Sub-contractors	Interest: To improve the existing operation, increase productivity, reduce cost, and to secure more call for tenders. Demand: Cost-effective, practical, innovative strategies, and appreciate the business model. New upstream and downstream industrial ecosystem. Incentives from the government. Impact: To promote innovation in the construction industry. To upgrade the future market.

Integrators	Interest: Collaboration, business expansion. Demand: Transparency in technology and interdisciplinary collaboration. Impact: To support innovation, and provide specialised services.
Manufactures	Interest: Collaboration, business expansion Demand: Transparency in technology and interdisciplinary collaboration that enhance the existing business. New upstream and downstream industrial ecosystem. Impact: To support innovation, and provide specialised services.
Suppliers	Interest: To provide existing services and products. To seek potential business expansion. Demand: Transparency in technology and interdisciplinary collaboration that enhance the existing business. New upstream and downstream industrial ecosystem. Impact: To support innovation, and provide specialised services.
Labour	Interest: Improved working condition, safety, and stereotype. Better equipped with innovative equipment. Continuing receive training and to improve skill levels. Demand: Improved salary yet eased the working process. Upskill personal skills and professional knowledge. Extended career path. Impact: To support innovation by identifying the functional and non-functional requirements.
Architects	Interest: To provide the existing services, to seek potential business expansion. Demand: Transparency in technology. Impact: limited influence items of OCR development due to unfamiliarity with the proposed technologies. Nevertheless, provide interdisciplinary collaboration where necessary.
Engineers	Interest: To provide the existing services, to seek potential business expansion. Demand: Transparency in technology. Impact: To provide practical solutions.
Competitors	Interest: Collaboration, transparency in technology, and avoid competition. Demand (Ambition): To be more successful or seeking mutual benefits. Impact: Stimulate innovation, speed up product iteration cycle, or obstructing business expansion and negatively affects the operation.
Public housing tenant	Interest: To secure a public rented or subsidised property. Demand: More public housing projects are to be constructed. Impact: limited influence items of OCR development due to unfamiliarity with the proposed technologies.
Stakeholder / Societal level	
Society & community	Interest: To make sure the development or activities related to the project will not cause social conflicts between different societies. Demand: Prosperity, human rights, and harmony in society. Impact: limited influence items of OCR development due to unfamiliarity with the proposed technologies.
Environment	Interest: To make sure the proposed operation will not negatively affect the environment. Demand: Strict rules and regulations are in place to oversee the proposed operation. Impact: Can either drive or hinder the innovation that depends on the outcomes of the development.

Disposition of the stakeholders:

The power-interest grid consists of four quadrants; each quadrant represents one type of stakeholder. The grids are divided by using two axes that point in the vertical and horizontal orientation. The vertical axis indicates the level of interests, and the horizontal axis indicates the levels of power. The upper two quadrants contain the stakeholder groups with the most of interest or have the most at stake. The one to the upper left is called the “Subjects” group that processes a low level of power, but a high level of interest. The stakeholders that belong to this group need to be well informed in regards to the development strategies. The project could improve their power base through alliance or government incentive plans, and policy changes, to move them into the "Key Player" group. The upper right quadrant contains the "Key Players", which holds the highest level of power and interest. They are the most important stakeholders, which need to be included in the development stage and to reach their expectation in all aspects. The lower two quadrants illustrate the stakeholder groups with the lowest level of interest. The lower left group "Crowd" belongs to the stakeholders that possess the least power and are least aware or interested in the project. This group can be seen as potential stakeholders, who require the least attention from the project team. The lower right group is called "Context Setters"; the stakeholders in this group can potentially influence the future context of the project, yet expressed a huge interest in directly engaging in the project. Lack of knowledge or understanding of the strategies proposed may lead to low-interest rates among the highly influential stakeholders.

Increased interest level can be achieved through project progress, demonstration and exploration (Ackermann and Eden, 2011). After carefully investigating the stakeholder power-interest grid, the project team allocated the stakeholders into the corresponding quadrant, see Figure 17.

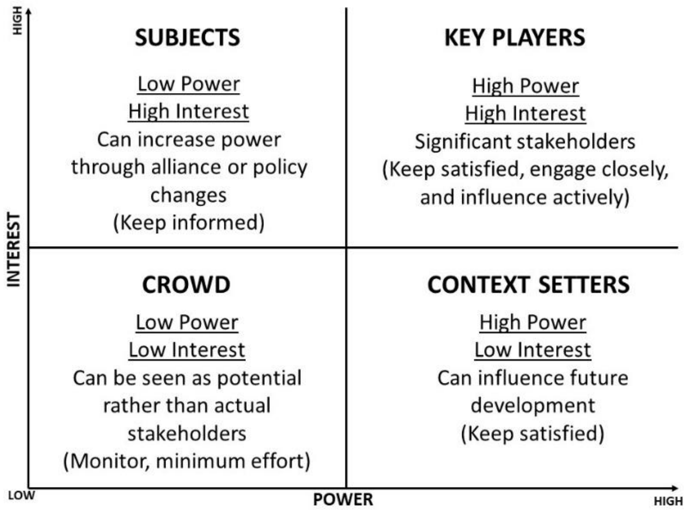


Figure 17: The four quadrants for the stakeholders.

As can be seen from Figure 18, some stakeholders appear in a combined grid. This area is marked by a dotted blue oval, and this overlapping area can be referred to as the "area of instability" (Ackermann and Eden, 2011).

For instance, contractors, service providers, and sub-contractors are located between "Subjects" and "Key Players". Here the author will use two examples to explain the concept of "area of instability". First, take the contractors as an example, even though they are highly interested in the proposed strategies, they cannot influence the "Key Players" in the beginning phase of the project. During the first phase of the project, the contractors are playing a collaborative role between the project team and the "Key Players", however, once involving them more deeply in the development stage the final product will take shape based on the requirements defined by them. By then, the position of the contractor will be shifted from "Subjects" to "Key Players". This does not mean they hold more absolute power, but that they should be considered as potential end-user, and the end-users orientation can influence the "Key Players" decision-making in terms of project development instantaneously (Narver and Slater, 1990). As a second example, the government agencies are situated in-between "Key Players" and "Context Setters", which represent authority and highly influential. However, at the beginning of the project, due to lacking the awareness about the proposed strategies, they appeared to be neutral or rather disinterested. Once the project has demonstrated some positive results, the success may draw their attention to be proactively engaging in future development. They will have huge implications on the success or failure of the project, therefore, once the government agencies acknowledge the project, they will move from "Context Setters" to "Key Players".

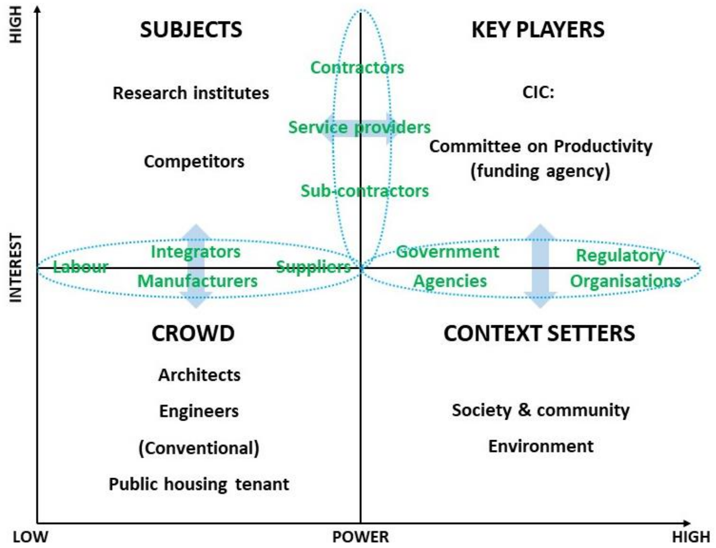


Figure 18: The stakeholders' power-interest grid.

Impact on practice in the different project phase, interaction:

As mentioned earlier, the stakeholder's objectives, interests, and requirements will influence the orientation of the project development. Their requirement for the final product also changes during the project development phases. Each stakeholder has a distinct influence that can become either a development driver or hindrance. Therefore, it is important to be aware of their relationships and to manage their requirements strategically (Robert G, 2011). In the CIC project, the product development drivers can be categorised as technological know-how, engineering, financial gain, market and customer gain, management strategies, operation, training, sales, logistics, marketing, competition, institutional, ethical, environmental, social, publicity, and supply chain evolution. The author would like to illustrate the different development drivers to the respective stakeholders in each project phase respectably see, Table 24.

Table 24: Development drivers for the stakeholders.

	Product development driver			
Stakeholder	**Phase one**	**Phase two**	**Phase three**	**Phase four**
CIC	Institutional, Management strategies, Publicity	Institutional, Management strategies, Publicity, financial gain	Institutional, Management strategies, Publicity, Training	Marketing, Social, Ethical, Publicity
Research institute	Technological know-how, Engineering	Technological know-how, Engineering, Management strategies, Marketing, Operation	Technological know-how, operation, Publicity	Management strategies, Publicity
Government agencies	Institutional	Institutional, social, Ethical	Institutional, social, Ethical	Institutional, social, Ethical, Publicity
Regulatory organisations	Institutional	Institutional, social, Ethical	Institutional, social, Ethical, Environmental	Institutional, social, Ethical, Environmental
Contractors	Engineering, management strategies, Supply chain evolution, Marketing	Engineering, Management strategies, Operation, Supply chain evolution, Marketing, Logistics	Institutional, Marketing, Training, Supply chain evolution	Institutional, Financial gain, Market & customer gain, Sales, Competition
Service providers	Engineering	Marketing, Supply chain evolution, Operation, Logistics	Marketing, Training, Supply chain evolution	Financial gain, Market & customer gain, Sales, Competition
Sub-contractors	Engineering, management strategies, Supply chain evolution, Marketing	Engineering, Management strategies, Operation, Supply chain evolution, Marketing, Logistics	Institutional, Marketing, Training, Supply chain evolution	Institutional, Financial gain, Market & customer gain, Sales, Competition
Integrators	Engineering	Operation, Logistics	Marketing, Supply chain evolution	Market & customer gain
Manufacturers	Engineering	Operation, Logistics	Marketing, Supply chain evolution	Market & customer gain
Suppliers	Engineering	Operation, Logistics, Supply chain evolution	Marketing, Supply chain evolution, Supply chain evolution	Sales, Market & customer gain, Supply chain evolution
Labour	Ethical, Engineering	Operation, Training	Training	Ethical
Architects	Engineering	Operation, Supply chain evolution	Institutional, Supply chain evolution	Supply chain evolution
Engineers	Engineering	Operation, Logistics	Training	Supply chain evolution
Competitors	Technological know-how	Technological know-how, Supply chain evolution	Competition	Competition,
Public housing tenant	N/A	N/A	N/A	Ethical
Society & community	Institutional, Ethical, Social	Institutional, Ethical	Institutional, Ethical	Institutional, Ethical

Environment	Institutional, Ethical, Environmental	Institutional, Ethical	Institutional, Ethical	Institutional, Ethical, Environmental

As the stakeholder analysis shows, this project has multiple types of stakeholders who have unique interests, share different relationships, and are influenced and affected by the product development drivers in the various project phases. The key stakeholders should be actively involved in the product development process. However, to address all stakeholders demands is difficult in practice, hence, it is important to prioritise the right amount of attention to the stakeholders based on the importance of their involvements and specific initiatives in the project phase (Majava, Harkonen and Haapasalo, 2015).

The method used for prioritising stakeholder is to categorise the stakeholders in a hierarchical order. The method is inspired by the product requirement engineering strategy introduced by (Ebert, 2008). The priority level has been given on a scale from one to five considering three factors: 1) how much the stakeholder may influence the project, 2) how big the impact of the project on the stakeholder is, or in reverse, and 3) how big the interest of the stakeholder in the project is. The overall priority value is the mean value between these three and has been given a further quality scale (low = (1, 2), medium = (3), high = (4, 5)). Finally, the key stakeholders, namely those with highest values, are highlighted in red, the one with medium values are marked in yellow, and the low values are indicated in light blue. This exercise can further validate the accuracy of stakeholder classification, which has been done in the previous stage, see Table 25.

Table 25: The hierarchical order of the stakeholders.

The hierarchical structure of the stakeholders					
Stakeholder	**Influence** (Scale: 1 to 5)	**Interest** (Scale: 1 to 5)	**Impact** (Scale: 1 to 5)	**Priority** (Scale: 1 to 5)	
CIC	5	5	5	5	High
Research institute	5	5	5	5	High
Government agencies	4	2	5	3.6	Medium
Regulatory organisations	4	2	5	3.6	Medium
Contractors	5	5	5	5	High
Service providers	3	2	2	2.3	Low
Sub-contractors	3	5	5	4.3	High
Integrators	2	2	2	2	Low
Manufacturers	2	2	2	2	Low
Suppliers	2	2	2	2	Low
Labour	3	2	4	3	Medium
Architects	2	1	2	1.6	Low
Engineers	2	2	2	2	Low
Competitors	3	5	3	3.6	Medium
Public housing tenant	1	1	1	1	Low
Society & community	2	2	2	2	Low
Environment	2	2	2	2	Low

The CIC committee on productivity is the funding agency of the project, and the customer. However, the end-user groups consist of contractors and sub-contractors. The advantage is that

CIC is closely associated with the end-user groups, which can provide valuable statistics and acquire communication between the end-users and the research institutes. Based on the analytical data, the author has divided the main development activities into four steps; they include requirement engineering, development, implementation, and product validation. Then the stakeholders are positioned in each step, the result indicates that CIC, research institutes, contractors, and sub-contractors are the most active stakeholders, because they are proactively engaged in each activity, see Figure 19. The result has verified the hierarchical structure that those four parties belong to the high priority group and the most influential. This approach helps the research team identify the potential relationship, conflicts, and expectations between the key stakeholders.

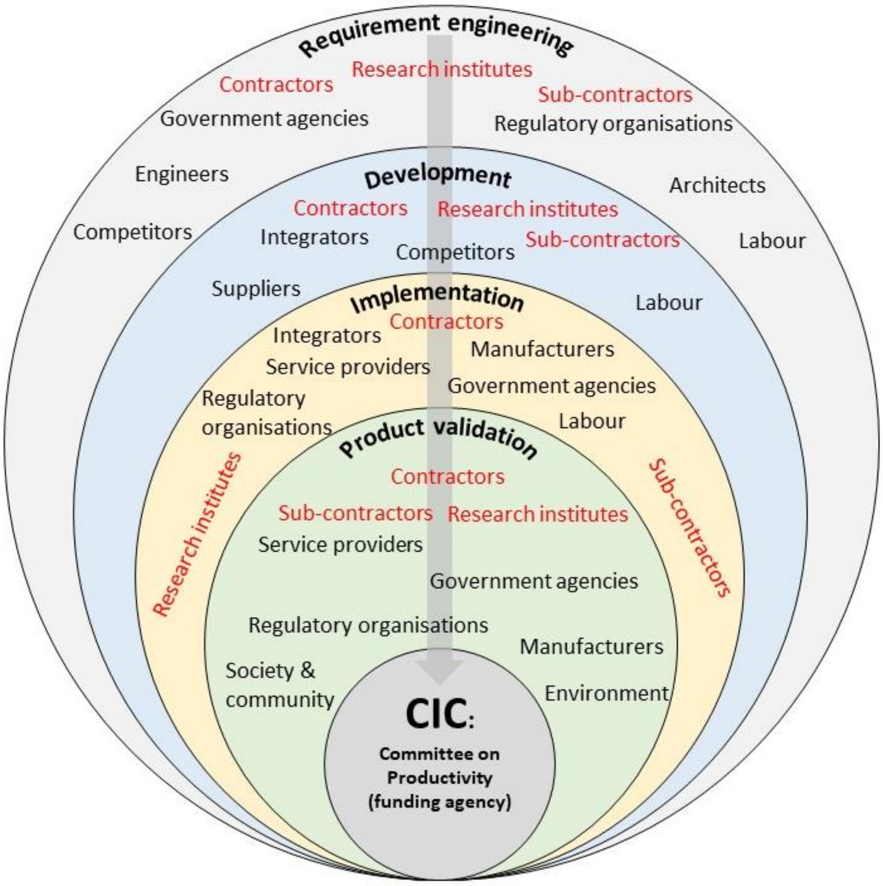


Figure 19: The main development activities.

The proposed OCR technology is to be considered radical innovation for the construction industry. The type of innovation is completely new to the industry; it will affect the cooperative strategies between the key partners (Allen, Booz and Hamilton, 1982). When dealing with such a new product, a single firm very rarely has the full competence or expertise to carry out the entire product development (Teece, 2008). Due to the unfamiliarity with the product, it is hard to attract partners with strong commitment unless there is a chance of mutually achieved benefit. In the case of OCR, as mentioned earlier, many stakeholders are involved in the product development stage, which requires the integration of designing, R&D, engineering, marketing, and implementation. The firm should obtain knowledge and technology that does not belong to the core competency of the firm externally. The development is prone to better results with the exchange of resources and knowledge and the focus on the competitive advantages (Bucklin and Sengupta, 1993). This will reduce huge development costs and share risks during the product development stage (Dickson, 1992). This approach has been put into practice in the CIC project, wherein CIC utilises its advantages by providing key information that the development requires. The research institute, TUM, provides technological knowledge, while the other key stakeholder supplies supporting information. To follow a clear product development focus is crucial, after understanding the interests, demand, impact, product development driver, and hieratical order of the stakeholders. The next step is to conduct initial requirement engineering that identifies and validate the requirements, then to plan how to communicate with the corresponding stakeholders.

3.2.2 Initial requirement identification

Identifying the initial requirements will ensure accurate decision-making, focused development strategy, and keep a smooth overall development process. Why must it be referred to as the initial requirements? This is because during the first stage of the project CIC and the key stakeholders are unable to provide concrete requirements due to unfamiliarity with the proposed technology. The identified initial requirements need to be refined and validated throughout the development. The requirements may evolve due to the changes of stakeholders' interests in each phase of the project, which means the requirements engineering process needs to be repeated at each project phase to ensure the correct attention is placed on the specific requirements. Online surveys, on-site visits, and co-creation will provide a variety of information to assist more specific requirement identification. Thus, the first step is to identify initial requirements based on the understanding of each stakeholder's perspective of the project: what are the practical objectives of stakeholders? What do they really desire from the project? Is it possible to quantify the requirements? Can the requirements result in any conflicts between the stakeholders? Can the requirements actually define what the customer or end-user wants? Is it possible to find a balance or intermediate requirement that will embrace the most of mutual benefit? The prioritization of the stakeholders will give an early insight of which requirements have more weight on the project, coming either from high-priority stakeholders or from the collective choices. There are five steps in the requirement engineering process. First, the team must write the initial requirement based on product development drive. Second, they will categorize the requirements into function and non-functional requirement. The third step is to prioritize the categorized requirements. Followed by step four: specification of the requirements. The final step is to validate the requirements.

Writing the requirements is the basic step of the requirements engineering method. The description of requirements should be precise, concrete and reflecting as much as possible the stakeholders' expectations derived from the stakeholder analysis. Each requirement should have a rationale that supports the background reason as well as mitigate any uncertainties (Robertson & Robertson, J., 2013). It is important the suggested requirements are measurable or quantifiable. Otherwise, it is difficult to indicate if the requirements are satisfied and the final design is the one that the stakeholder wanted. The author's method is to analyse and use the predefined drivers of product development as the initial source of requirements. Even though the product development drivers are presented in a rather broad sense, it offers a good indication which action the specific stakeholder is interested in. Taking “Technological know-how” for example, it will be elaborated as: the end-effector is changeable; the robot is compatible with the existing tools, or integrated material supply system.

Usually, as the client, CIC should declare clear requirements in the early stage of the project that helps structure project objectives and define the development focus. Nevertheless, this is if the customer is familiar with the new technology. However, this is not the case in the CIC consultancy project; the description of the task is to investigate the potential of implementing robotics and automation in the context of large-scale housing development for Hong Kong. This is an extensive topic, so it is hard to predict what the outcomes are going to be, especially at the early stage. As mentioned earlier, phase one is has been divided into four stages, and the aims of the first stage are:

- To explore and analyse what challenges the Hong Kong PHC sector is facing
- To identify which task can be optimised by adopting automation and robotics technology
- To define the stakeholder’s functional and non-functional requirements in regards to on-site construction robotic implementation in the Hong Kong PHC sector

The aims for the rest of the project stages will be illustrated in the correlated section. The initial requirements were mainly based on past experience, discussion with the CIC project team, correlation with related sectors or goods, and literature review. Even though this is a challenging task, this task provides an opportunity to define requirements for a project that potentially will evolve from merely consultancy tasks to development of one or a range of practical OCR systems. Table 26 represents the categories of the initial requirements. These are comprehensive and need to be identified as more specific requirements once the project team achieves an oriented path of development.

Table 26: The initial requirement identification.

Initial requirement identification	
Category	**Description**
Technological	Requirements associated with technical, design, engineering, operation, management, integration, implementation, health & safety, and logistic aspects.
Economical	Requirements are related to marketing, business model, operation, and incremental value-added benefits.
Institutional	Requirements concerning regulatory compliance, certification, decision making, health & safety, and organisational aspects.
Ethics & Social	Requirements regarding individual rights, privacy, transparency of development, training, health & safety, and human factors.
Environmental	Requirements respecting operation condition, environment impacts, and legal requirements relating to the environment.

The next step is to define the initial functional and non-functional requirements by using the categorized initial requirements. This method is commonly used in software development. In general, functional requirements specify what the product must do and describe what the project has to do to support stakeholder's work. They are usually quantifiable and aim to a specific goal, which can be a particular behaviour or output of the system. Non-functional requirements express the quality of the project and therefore they are not always countable or easy to assess. They put constraints on functional requirements and help concretely define and tailor them to the end-user need (Capilla, Ali Babar and Pastor, 2012). In the context of the CIC project, the initial functional and non-functional requirements can be derived from the following aspects:

The requirements have been separated according to the system level, development level, the system level emphasising product-related aspect. The development level focuses on product developing associated issues, such as marketing, social, and regulatory.

Initial functional requirements:

- Technological specification: Targets the system level. Concerning system features, DOF, functions, hardware-software integration, size and weight of the proposed system.
- Constructability: Targets the system and development level. Focuses on if the proposed system can be built, tested as mock-up, prototype or mass-produced.
- Compatibility: Targets the system level. Regarding compatibility with the existing infrastructure, system, and skillset.
- Productivity: Targets the system level. Targeting construction speed, upskill labour, improving construction quality, safety, and saving construction cost.
- Mobility: Targets the system level. Observing system flexibility, manoeuvrability, stability, positioning, and logistics issues. These requirements can be considered as a subcategory of the technical specification requirement.

Initial non-functional requirements:

- Usability: Targets both the system and the development level. Concerning if the intended audience can operate the proposed product with the existing skill level. If the current infrastructure is able to support the system operation
- Performance level: Targets the system level, considering how fast, accurate, reliable, scalable, durable, and tolerant the proposed system should be.
- Operational: Targets the system level. Determining the intended operating condition.
- Maintainability: Targets the system level. Reviewing if the proposed system can be repaired, and maintained conveniently. If the maintenance method or equipment is compatible with the building and going to cause any conflicts with other requirements.
- Supply and support: Targets the development level. Looking into the existing supply chain, and support network.
- Training: Targets the development level. To check if adopting the proposed system with the existing labour force requires additional training.
- Business and marketing: Targets the development level. Evaluating what type of business model is appropriate for the key stakeholders.
- Cultural acceptance: Targets the development level. Concentrate on human and sociological factors. If the proposed system is socially, morally acceptable.

- Security: Targets the development level. In this case, the focus differs from health and safety. Emphasising on privacy and confidentiality issues during project data transfer process. In addition, to predict any potential risk imposed by system information and communication transaction process.
- Health and safety: Targets the development level. Convening safety issues that relate to construction accidents, precaution measure, health-related hazards, planning, supervision, and preparation of work.
- Regulation and legislation: Targets the development level. Focusing on if the proposed system will comply with the existing regulations, and if it is necessary to impose new legislation.
- Certification: Targets the development level. Concentrating on analysis what type of certification or standard is required when introducing such innovative product into the market.
- Sustainability: Targets the development level. Addressing issues related to product recycling and product life-cycle management.
- Environment: Targets the development level. Concerning the operational environment. If the proposed system can reduce pollution, noise level, material use, and to avoid human contact with toxic chemicals.

Many of the requirements above should be identified through the detailed development stage, by conducting use case scenarios on the chosen stakeholders. Some can only be verified over extensive pilot testing. Therefore, with the current information in hand, it is still too early to define detailed requirements. The more precise requirements that are relevant to the development can be attained after narrowing down the development focus accompanied by applicable use cases, or scenarios. Narrowing down the research focus implies extensive communication and data collection that is closely accommodated by the key stakeholders. The detailed communication and data collection methods, which include an online survey, on-site visit, and a co-creation workshop, will be described in detail in the following sections.

3.2.3 Potential challenges and conflicts

Stakeholder analysis has become a popular tool for decision-making that helps the project team gain an insight into the stakeholder’s interest, contribution, impact, and priority. However, in some cases, the project team may feel less motivated to conduct a stakeholder analysis. The reasons why a project team may feel hesitant to carry out stakeholder analysis include the following conditions.

Knowledgebase: Sometimes depending on the professional competence of the project team, perhaps the task is too difficult for them. Another case would be the project team considers they are already fully aware of the stakeholders and do not need to spend time and effort conducting the task.

Resources: The project team might consider there is not enough time or resources to conduct the task, or feel there is not enough information for the stakeholder to respond.

Reality: Sometimes, the stakeholder analysis will unveil the reality, and the facts may differ from the predicted outcomes. This is somewhat demoralizing in the early stage of a project.

Ethical: In some cases, the project team considers the stakeholder analysis is less comprehensive and involves a reinterpretation of some confidential materials, especially if the communication with the stakeholder is restricted (John M. Bryson, 2003).

The conflicts of interests fall between the industry and the institutions. For instance, the current policy and building regulations were drafted based on traditional construction methods, which will impose some constraints for construction automation and robotic transformation. The difference in interests between academia and the industry can lead to conflicts in the views of research excellence versus practicality and applicability.

3.2.4 Impacts and Summary

This section emphasizes the importance of stakeholder analysis; a systematic approach was illustrated based on the data gathered from the first stage of the CIC consultancy project. A detailed method was introduced to identify the initial requirements based on the understanding of each stakeholder‘s perspective of the project. In terms of OCR development, due to the key stakeholders not being familiar with the proposed technology, the project team should provide guidance about the proposed technology that ensures the accuracy of the feedback when carrying out a stakeholder analysis. This situation makes conducting requirement identification a very challenge task, yet to identify stakeholder’s requirements in an early stage will ensure accurate decision-making, focused development strategy as well as to deliver a product that customer has demanded. The following sections will illustrate the data collection methods applied by the author to define development direction, priority areas, and to narrow down design choices.

3.3 Online survey

There are many ways to collect data for project development, such as surveys, interviews, observations, workshops, emails, and telephone calls. Each method contains its own strength and weakness, and, therefore, it is important to select the most appropriate approach to target various research scopes, target audiences, and the nature of the data. In the CIC project, based on the initial research, the project team experiences some degree of challenges in regards to how to identify functional, and non-functional requirements of the proposal. This is due to most of the key stakeholders being unfamiliar with the proposed technologies. The purpose of the survey is to gain different insights of the key stakeholder’s opinions about automation and robotics technologies, and based on their experience to evaluate whether or not to implement OCR and, if so, which one is appropriate for the Hong Kong PHC sector. In addition, it is planned to examine the feasibility of those technologies and the potentials to improve productivity, safety, and quality performance of the industry. However, before starting design, draft, and distribute the survey, it is essential to provide sufficient information on the subject of the project in order to guide the target group from understanding the context of the survey.

3.3.1 Method

A comprehensive introduction booklet was produced before the online survey and distributed among the selected stakeholders. At this stage, the targeted stakeholders consist of influential industry practitioners, academics, architects, Non-Governmental Organizations (NGOs), and the local authorities. The booklet serves as an eye-opener for the construction industry due to the unfamiliarity of robotic technologies. It also assists the stakeholders in understanding the project objectives, and to demonstrate the potential application, which can be applied in the Hong Kong PHC sector. A background study was conducted according to the materials supplied by CIC that focused on the public rental housing development contracted by Hip Hing Engineering Co., Ltd at Ex-Kwai Chung Police Married Quarters building. Based on the findings from the background studies and internal discussions between TUM, CIC and key stakeholders, 22 robotic and automation systems were proposed. The 22 selected systems were also systematically distributed into three use case scenarios (Kevin, Mooz and Cotterman, 2000), see Figure 20.

Figure 20: The background study and the proposed scenarios.

The scenarios were envisaged based on the evolution of the degree of automation, and their ability to be integrated into the industry during the course of the proposed development roadmap. The first scenario aims to demonstrate the potential of OCR. To assist profession-specific, physically demanding and repetitive tasks on-site. Under this scenario, there are limited alterations, which the existing building has to adopt. There is a modest impact on the conventional construction industry and the structural performance of the building. It also serves as the backbone for future development. The second scenario integrates automatic and semiautomatic construction systems. In this scenario, some of the proposed solutions may require alteration of the existing building design. For instance, a higher degree of prefabrication rate is recommended. The building method may need to adopt the use of robotics and automation. The third scenario illustrates the potential of applying a fully automated construction system in Hong Kong. In this scenario, the proposed solution can be applied only if the building is designed in consideration of the ROD. This scenario describes the ultimate goal that can be achieved when applying feasible automation and robotics technologies in the construction industry in Hong Kong. The scenarios also functioned as project use cases that allow the stakeholder to be aware of the potential time-line and implication on the traditional construction industry when implementing automation and robotic technologies. Ultimately, the booklet is an effective tool to engage the stakeholders, especially when they are in possession of very little previous experiences and knowledge about automation and robotics in construction (Pan, Wen *et al.*, 2018).

The online survey will be conducted using a web-based survey method. There are many advantages of a web-based survey, such as low cost, fast distribution, better visual impacts, automatically generated database, and eliminating transcription errors. However, there are some drawbacks, for example, low response rate, privacy, and confidentiality concern. Therefore, to enhance the outcome of the survey, the project team has to choose relevant target audiences, to protect their privacy, to distribute the survey in the correct manner, to develop the survey in a way that will grab their attention, and to encourage the user to follow and to complete the entire survey (Dorine, Blair and Jennifer, 2007).

In this stage of the project, TUM worked closely with CIC to define the target groups, in which most of the selected parties are the recipients of the booklet. Booklets were also sent out to those parties of whom are not targeted, yet are considered as highly relevant. In the end, over 200 professionals were selected as the target group. An informative and formal invitation email, as well as a complimentary letter, was distributed, which contains information about the background of the project, purpose of the survey, expected time to complete the survey and to express the gratitude of their involvement. The online survey (powered by Google Forms), see Figure 21 is designed with consideration of the following principles, first, from both the content and the graphical user interface (GUI) aspects the survey needs to be designed easy to follow by audiences that acquire very few knowledge about the given topic.

Second, it is also designed to encourage the user to express their point of view, yet to prevent multiple submission (Yun and Trumbo, 2006). Third, the questions are kept short, logical, and require minimal completion time (Kehoe and Pitkow, 1996). Fourth, it is designed to protect their privacy against potential identity thief (Cho and LaRose, 1999).

In terms of the design, the survey adopted a less offensive light green colour tone. The title of the survey is “Survey on Potentials of Implementing Robotics and Automation in Housing Development for Hong Kong”. The mandatory field was clearly indicated with (*required) in red. The purpose of the survey is introduced briefly at the beginning of the survey. The participant is requested to provide their personal information including their name, position, years of experience in the industry, email and contact details. The only mandatory field in this section is the identification of the stakeholder group, which they have to indicate in the appropriate category. The available categories include client body, consultant, contractor, policymaker, and others. A disclaimer indicated that the personal information entered here is only for statistical reasons, and the project team will not share, sell or rent the personal data to any other parties. Questions were based on the selected 22 robotic and automation systems. A graphic icon that represents the system was designed, followed by an image and a short video to attract the attention and to offer as much information as possible.

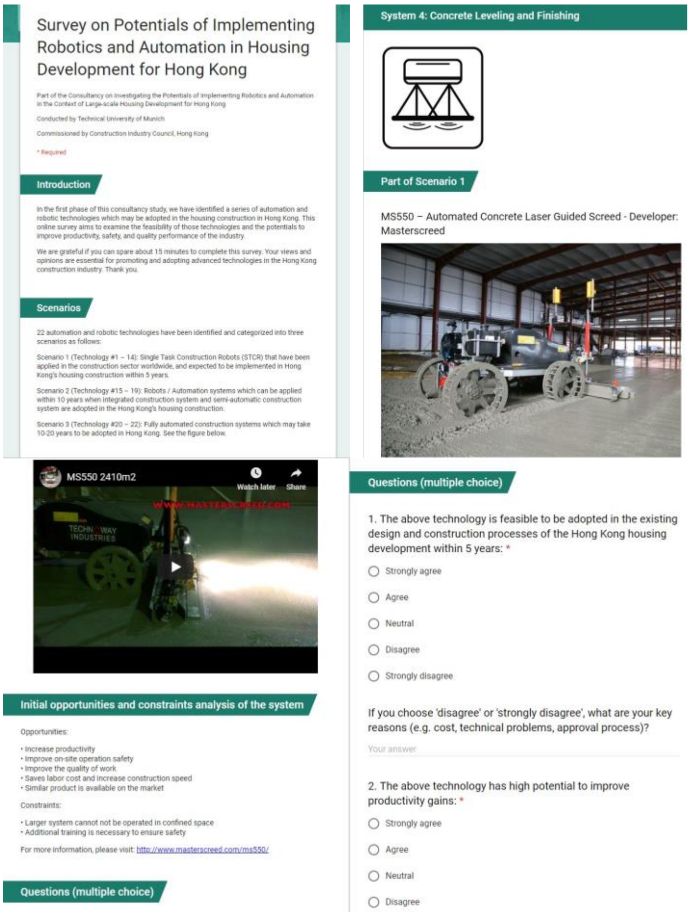


Figure 21: The design of the online survey.

The predicated system opportunities and constraints were illustrated. Furthermore, if the participant would like to access more information on the system, a link to the official website has been provided. The questions consist of mainly agree/disagree questions followed by an open-ended question. The answer is structured on the weighted value, for example, strongly agree, agree, neutral, strongly disagree. The open-ended question is dedicated to those ones who choose “disagree” or “strongly disagree” to provide additional comments. There are four questions assigned to each system including:

1. The above technology is feasible to be adopted in the existing design and construction processes of the Hong Kong housing development within 5 years
2. The above technology has high potential to improve productivity gains

3. The above technology high potential to improve safety and working conditions
4. The above technology has high potential to improve building quality

The author estimated it would take approximately 15 minutes to complete the entire survey. The 22 selected construction robots that are featured in the survey include, see Table 27:

Table 27: The selected construction robots for the survey.

T1	Reinforcing bar fabrication positioning	T12	Automated interior tiling
T2	Automatic climbing formwork	T13	Robotic marking
T3	Concrete distribution	T14	Exoskeleton
T4	Concrete levelling and finishing	T15	Mobile on-site factory
T5	Logistics supply	T16	Vertical delivery system
T6	Hoist and positioning	T17	Building components positioning and handling
T7	Installation and material handling	T18	Façade element installation
T8	Façade cleaning and exterior finishing	T19	Prefabrication in the HVAC system
T9	Interior painting	T20	Sky factory
T10	Interior wall plastering	T21	Ground on-site factory
T11	Automated bricklaying	T22	Integrated on-site assembling system

The survey follows a two-round selection method (Nanyam *et al.*, 2015), see Figure 22. The first round is to examine the feasibility of these technologies (the primary attribute). Once accepted, all attributes of these technologies (e.g., feasibility, improvement of productivity, safety, and quality), are further examined. Each question is based on the Likert Scale (Likert, 1932). In addition, survey participants can also leave additional comments on each technology.

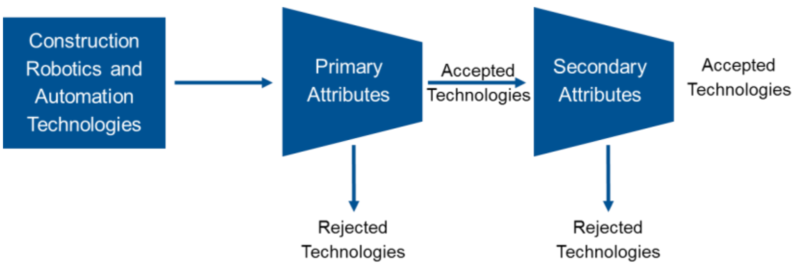


Figure 22: The two-round selection method, according to (Nanyam *et al.*, 2015).

The following is the equation followed for calculating the TPS of the attributes of each technology:

$$\text{TPS} = \sum_{i=1}^{5} Pi \times Wi$$

TPS = Technology Preference Score

P = Percentage of Preference

W = Weighted Value (strongly agree=100; agree=75; neutral=50; disagree =25; strongly disagree=0)

i = Likert Scale

3.3.2 Online survey results

The online survey was sent out to more than 200 professionals/stakeholders from the Hong Kong construction industry, and 36 effective survey responses were received. Professionals are from various backgrounds; 36% of the participants are contractors, 28% are consultants, 14% are clients, 14% are policymakers, 5% are academics, and 3% are NGO members. 82.4% of participants have more than 10 years of experience in the construction industry. After calculating the survey data according to the aforementioned method, the survey results of the two-round selection are listed below, see Figure 23 and Figure 24. Technologies with a score above 70 are strongly/highly recommended; between 50 and 70 are recommended; below 50 are poorly or not recommended. In the first-round feasibility examination, the logistics supply and ground factory on-site are visually excluded by a red slash according to the criteria (because their feasibility scores are below 50).

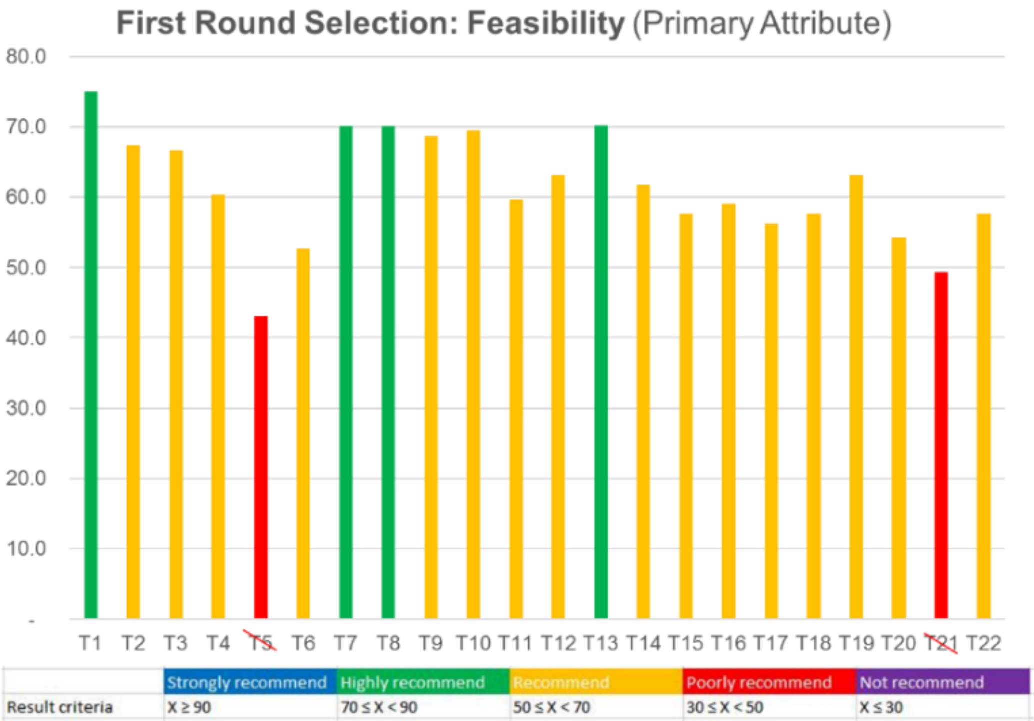


Figure 23: The results from the feasibility round.

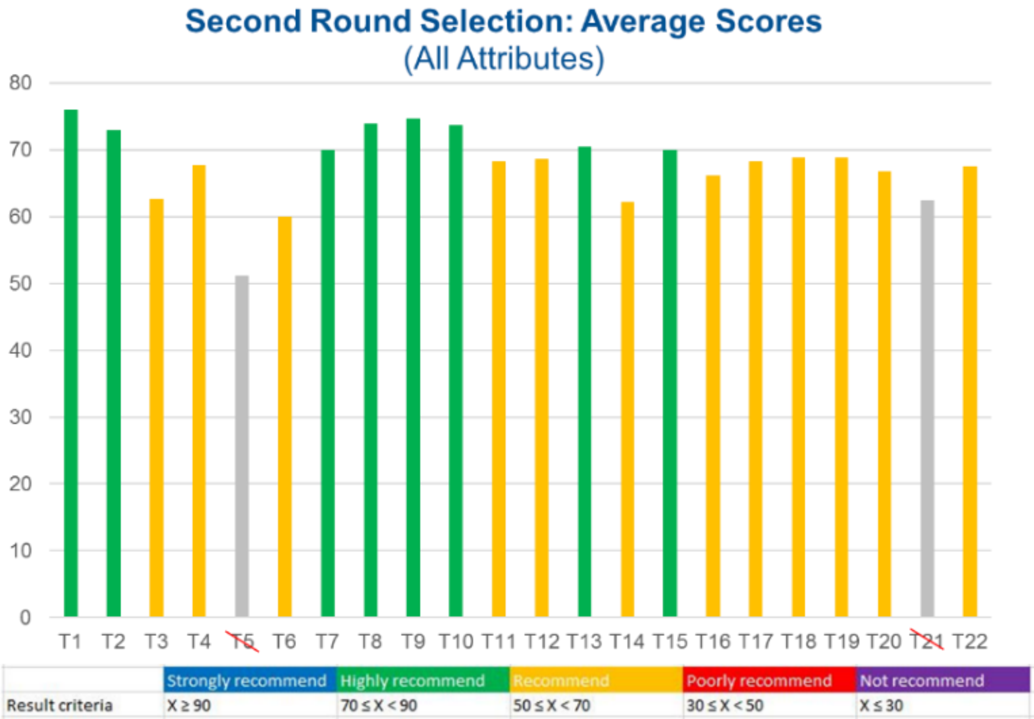


Figure 24: The results from the second round selection based on all attributes.

Highly Recommended Technologies	T1 (Reinforcing Bar Fabrication/ Positioning) T2 (Automatic Climbing Formwork) T7 (Installation and Material Handling) T8 (Façade Coating, Painting, Cleaning and Exterior Finishing) T9 (Interior Painting Application) T10 (Interior Plastering Application) T13 (Robotic Marking) T15 (Mobile On-site Factory)
Recommended Technologies	T3 (Concrete Distribution) T4 (Concrete Leveling and Finishing) T6 (Hoist and Positioning) T11 (Automated Bricklaying) T12 (Automated Interior Tiling) T14 (Exoskeleton) T16 (Vertical Delivery System) T17 (Floor Slab, Beam, Column Positioning and Handling System) T18 (Facade Element Installation) T19 (Prefabrication in HVAC System) T20 (Sky Factory) T22 (Integrated & Automated On-site Assembly System)
Rejected Technologies	T5 (Logistics Supply) T21 (Ground On-site Factory)

Figure 25: The final results of the online survey, according to (Pan, Wen *et al.*, 2018).

In conclusion, the result of the two-round selection summarized in Figure 25 shows that in Hong Kong, the local professionals and stakeholders overall approve the construction robotics and automation technologies. The highly recommended technologies are of high priority, and thus can be implemented in the near future. The recommended technologies are also demanded, but there is a long way to go before they can be fully implemented. However, based on the survey result, some technologies are not feasible at the moment, such as T5 logistic supply and T21 ground on-site factory.

3.3.3 Impacts and summary

The booklet has introduced the key stakeholders to a detailed description of the state of the art construction automation and robotic technologies. The selected technologies were assigned into several scenarios, which were based on the evolution of the degree of automation, and their ability to be integrated into the Hong Kong construction industry during the course of the proposed development period. One of the most obvious impacts by conducting the online survey is to achieve an overall insight on the views about selected construction robots and to obtain recommendations on which system in their opinion should be prioritized. As mentioned earlier, the survey received 36 positive respondents, and the results are similar to the predictions made prior to the survey. However, logistic supply technology was initially considered as highly valuable for on-site construction activities, yet was eventually rejected by the participants. Consequently, the project team believes further data collection with multiple sources of verification methods are needed to acquire a different type of data that shall validate the survey result as well as to yield alternative insights (Rowley, 2002). As a result, an on-site visit was conducted with the focus of a typical Hong Kong PHC site; the next section illustrates this activity in detail.

3.4 On-site visit

Shortly after the online survey, the author travelled to Hong Kong to conduct a comprehensive on-site case study, which was organized by CIC and Hip Hing Engineering Co., Ltd. The site is located on Ngan Kwong Wan Road in Mui Wo, Hong Kong, and it consists of two residential building blocks (one 14-storey and the other 16-storey), both of which are designed as Home Ownership Scheme projects, as shown in Figure 26. The load-bearing structure, such as the shear wall structure is cast on-site with conventional formwork. The non-load bearing façade is made of precast reinforced concrete, and prefabricated off-site.

Since the case study buildings were close to the completion stage, limited site activities could be observed. Thanks to the collaboration of the Hip Hing Engineering Co., Ltd, the author was able to access the site diary and the construction imagery folder, which documents the entire construction sequence to date. The main objectives of the on-site study are as follow:

- To understand current workflows, techniques, regulations, and tenders process of the existing PHC sector.
- To identify KPIs that measure construction success of the project.
- To discuss and exchange ideas with the site manager, skilled labour, and contractors in regards to the implementation of construction robotics in Hong Kong.

Figure 26: Snapshots of the on-site visit, and the case study building.

- To determine which working process can be potentially automated.
- To identify what are the functional requirements of the identified systems.
- To map out feasible concepts and roadmaps for future development.

The on-site visit provides an explicit opportunity to validate the accuracy of the previous study, furthermore, to acquire direct feedback from the stakeholders that are working on-site.

3.4.1 Method

The on-site visit lasted for 12 days, consisting of interviews, observations, and documentation of the daily discover. In Hong Kong, every person who is working on-site must hold a "Construction Industry Safety Card", or "Green Card Training Course". However, the applicant must have a valid working visa and permanent residency in Hong Kong. The author is not eligible to take the training course so the site manager has to assign a member of the team to escort the daily visit. During the first two days of the visit, a detailed tour was conducted, supervised by the site staff. During the tour, the site staff demonstrated job site layout, composition of the construction crews, health and safety measures, and recycling facilities. The site and work tasks were well organized and planned in a conventional manner. On the other hand, it is very congested; there is limited space for material storage and vehicle manoeuvring. The finished floor spaces were also utilised for material storage. Same as many other PHC sites, this site follows a tight seven to eight days construction cycle; the reason that the site did not follow the more common six days cycle is due to the remote location of the site to the Hong Kong main islands. Extensive meetings and interviews were conducted between the author and the site manager, engineers, labour, and sub-contractors. The purpose of the interview is to understand the current workflow and constraints and whether it can be improved by implementing automation or robotics. The selections were made under the following considerations: if the on-site task is repetitive and/or labour intensive, if the task is prone to human error, if the task is costly both finically and physically, if the task subject to the skilled labour shortage, and if the task imposes significant safety hazards. The initial feeling from the interview is that the construction practitioners are sceptical about adopting robots on-site. This is because they are not aware of the potential of what robots can do on-site. The perception of construction robots is often to be portrayed as humanoid robots or industrial robots, which leads to concerns about costs and applicability. To solve this issue, the author prepared a brief introductory presentation along with conceptual designs as a virtual representation of some discussed robotic system. By doing so, the interviewees can understand the proposed technologies comprehensibly. The results of the on-site investigation can be seen in Table 28. The results are based on the subjective views of the interviewees.

Table 28: The on-site visit results shall be scored from low to high, and based on the probability of the task that can be automated.

On-site task investigated	**Opportunities when it is automated**	**Main constrains for automation**	**Potential to be automated**
Reinforcing Bar Fabrication/ Positioning	Improve productivity, quality of work	Lack of space on-site, Research investment	Low
Formwork installation	Increase speed, improve safety	Lack of space on-site, Research investment, difficult to validate	Low
Logistic supply	Improve productivity, safety	Lack of space on-site, heavily rely on suppliers, cost	Low
Hoist, positioning	Increase speed, improve safety	Difficult to validate, the existing method is very mature and fast, cost	Medium
Material handling	Improve productivity, safety	Difficult to validate, lack of infrastructure, the existing building is not adequate to support the additional weight, cost	Low
<u>Façade work, painting, preparation</u>	Improve productivity, safety	Research investment, technology integration	High
<u>Interior painting</u>	Improve productivity, quality of work	Research investment, technology integration, manoeuvrability	High
<u>Interior plastering</u>	Improve productivity, quality of work	Research investment, technology integration, manoeuvrability	High
Interior tilling	Improve productivity, quality of work	Limited space where requires tilling application	Low
Marking	Improve productivity	Difficult to manoeuvre & navigate high research investment	Low
Welding	Increase speed, quality of work, and improve safety	Research investment, technology integration, limited demand	Low
Mechanical and electrical (M&E) Works	Improve productivity, quality of work	Research investment, technology integration, manoeuvrability	Medium

There are few on-site tasks that were investigated extensively, in which five of them were considered worth automating. They include hoisting, positioning, façade work, interior painting, interior plastering, and M&E works, in which the façade work, interior painting, and interior plastering have the higher potential to be automated. The objective of the next step is to analyse these three tasks in detail. The detailed workflow, work method, amount of involved labour, time, and cost needed for the task was investigated.

1) The existing methods for exterior façade coating and painting are described as below: Façade surface condition:
    - Coating works will be carried out under suitable conditions of weather, temperature, humidity, ventilation and illumination at all stages to ensure quality can be maintained.
    - Ensure a suitable condition for coating. All surfaces need to be dry. Substrate moisture content is to be 15% or below and protimeter can be used for moisture measurements.
    - Regard environmental conditions: Coating should not be applied in temperatures below 10 °C and when the Relative Humidity exceeds 90%.

After the exterior façade is well prepared, three layers of coating will be applied. They are the primer coat, texture coat, and topcoat. The specification of the three coatings are:

a) Primer Coat (Water-Based Primer Coat): Apply one coat of "Biofine Sealer" to the whole surface by roller/ brush/ spray.
    - Consumption: 0.15kg / m^2/ coat
    - Interval Curing: Over 2 hours
    - Mixing Ratio: Biofine Sealer/ clean water, -20 ltr / 5% by weight
b) Texture Coat (Water-Based Acrylic Resin Texture Coat): Apply one coat of "Lena Luck" to the whole surface by spray.
    - Consumption: 0.45kg / m^2/ coat (fine texture), 0.85kg/ m^2/ Coat (medium texture)
    - Interval Curing: Over 24 hours
    - Mixing Ratio: Lena Luck/ Clean water, -26 kg/ 2 -5% by weight
c) Top Coat (Water-Based Acrylic Resin Color Protective Top Coat): Apply two coats of "Acristar Century" to the whole surface by roller/brush/spray.
    - Consumption: 0.15kg / m^2/ coat
    - Interval Curing: Over 2 hours
    - Final Curing: Over 24 hours
    - Mixing Ratio: Acristar Century/ Clean water -20 ltr/ 5% by weight

The amount of labour, time, and cost of the exterior façade coating and painting task are documented, see Table 29 :

Table 29: Task analysis of façade coating process.

Task	Labor	Time	Cost
Installation of the Gondolas X 40	3 workers	2 weeks	1000 HK$ per labour per day
Cleaning and preparation of the external wall, skim coating of the wall	3 workers	Up to 4 weeks	1300 HK$ per labour per day
Inspection work	1 foreman	Half-day	1000 HK$ per labour per day
Primer coating	2 workers	4 days	1300 HK$ per labour per day
Inspection work	1 foreman	Half-day	1000 HK$ per labour per day
Texture coating	1 worker	1 day (per section of the wing)	1300 HK$ per labour per day
Inspection work	1 foreman	Half-day	1000 HK$ per labour per day
Top coating	6 workers	3-4 month	1300 HK$ per labour per day
Inspection work	1 foreman	Half-day	1000 HK$ per labour per day
Dismantling of the Gondola	3 workers	2 days	1000 HK$ Per labour per day
Note: The data accumulated is based on the block-A building (16F) on the case study site.			

The current task is labour-intensive and imposes many health and safety hazards. The worker is stationed inside the Gondola, which is suspended at great heights. Falling from high elevations is one of the causes of fatal accidents on the construction site. Due to wind, the Gondola will swing repeatedly, External influence may widen the gap between the gondola and the façade. Therefore, it is difficult to reach certain areas where the paint needs to be applied. Furthermore, the painter has to wear a protective facemask, and clothing to protect against the flying paint particles. Astonishingly, there are only two registered painters working on-site, and the project manager mentioned that it is extremely difficult to recruit painters due to the lack of skilled labour industry-wide. Based on the data collected on-site, the author considers the façade finishing task has high potential to be improved by implementing automation and robotics technologies. The detailed functional requirements were discussed between the author, the contractor, and the project manager in detail towards the end of the on-site visit.

2) The existing methods for interior painting are described below, see Table 30.

Table 30: The existing methods for interior painting.

Description of the paint	MATEX AA EMULSION
Type	Acrylic PVA Copolymer emulsion coating
Colour	Standard colour as per colour card, subject to the design specification
Finish	Matt
Uses	Interior walls, Ceilings, Hard and soft boards
Features	Super valuable emulsion paint, Economical

	Washable (Wet scrub complies to ASTM D2486:96 Minimum 400 cycles) Fungus – Resistant Smooth appearance and easy application

Task application data of interior painting, see Table 31:

Table 31: Task application data of the current interior painting task.

Method	Brush, roller and airless spray
Theoretical Coverage	Theoretical – 13.3m^2/Liter Practical – Depends on substrate condition, application method etc.
Dilution	Use Clean water Brush – 15 – 30% Roller – 15 – 30% Spray – 15 – 30%
Surface Preparation	Ensure that the surface is clean and dry, free from oil, grease, algae, fungus and other foreign matter. Remove unstable paint film from the previously painted surface. Do not apply when moisture content above 6% or 19% determined by Protimeter. For new surface, Vinilex 5101 Wall Sealer or Odour-less All-in-one Primer or Ultra Sealer III is recommended for optimum results. Do not apply in a poorly ventilated area, high humidity above 85% and cool weather <5°C
Drying Time	Touch Dry – 10 Mins Hard Dry 30 Mins Overcoat Time – 2 Hours
Cleaning	Wash all equipment immediately with clean water after use

The task analysis of the interior painting, see Table 32:

Table 32: Task analysis for interior painting task.

Task	Labor	Time	Cost
Repair concrete wall surface	2 workers	2 weeks	800 HK$ per labour per day
Cleaning and preparation of the interior wall	3 workers	1 day	800 HK$ per labour per day
Painting X 3 coats	2 workers	1 week	1200 HK$ per labour per day
Note: The data accumulated is based on the block-A building (one wing) on the case study site.			

The current task is repetitive and painters are exposed to fine dust particles. The paint is applied by using roller and brushes. The task contains lower safety risks compared to exterior painting and can be enhanced by adopting automation and robotic technologies. The current condition imposes some constraints for implementing OCR in this case, because the job site is very congested, and building materials and tool are placed randomly across the operational space. Hence, when adopting OCR, the site needs to be well maintained, and the obstructions need to be cleared off from the OCR travel path prior to operation.

3) In the case study building, the locations that require plastering are the areas where tiles will be applied. The only areas that have tile coverage are the communal areas outside the passengers lift. The existing methods for interior plastering are described below, see
4) Table 33:

Table 33: Task analysis of the interior plastering application.

Task	Labor	Time	Cost
Repair concrete wall surface	2 workers	2 weeks	800 HK$ per labour per day
Cleaning and preparation of the interior wall	1 worker	1 day	800 HK$ per labour per day
Apply spatterdash	1 worker	2 days	1000 HK$ per labour per day
Rendering (plastering)	2 workers	1 week	1200 HK$ per labour per day
Note: The data accumulated is based on one wing in the case study site.			

Similar to interior painting, plastering work is repetitive, imposes minor health hazards, and the site condition is congested. In addition, from a technical point of view, the industry requirement for plastering is to achieve 15mm thickness in Hong Kong. Applying spatterdash and plaster takes specific training that the labour has to have, including a good command of hand tools such as trowel, hawk, skimming spatula, feather edge, as well as having good knowledge about material composition. Carrying out the task also requires good body coordination, good control of timing and precisions. Therefore, automating these tasks will be more challenging than the exterior painting task, but it is achievable depending on the work process that is chosen to be automated.

3.4.2 Outcomes

The project manager and sub-contractors hold an optimistic view of adopting automation and robotics on-site. However, the project manager also expressed some concerns; first, the robot should not simply replace human labour, but complement it. Second, the proposed robot needs to be compatible with the existing regulation, site condition, equipment, and construction method. Third, a single trade does not carry out most of the construction tasks, yet they are intervened by other professions. This might impose some difficulties when involving robotics, as it may increase the risk of one trade while benefiting the others. He also pointed out that the conventional construction process is very complex so that the designer must concentrate at the start of the most important part of the process in order to simplify the entire process. The on-site labourer is also enthusiastic about the topic, having the major concern of whether the proposed system is easy to operate or not. Surprisingly, they are confident that the robot can hardly replace human work, at least in the short-term perspective.

The adversarial mentality and fragmentation of the construction industry were evidently presented over the site visit. The author asked the project manager why the prefabricated façade panels were not painted off-site. The reason is that the prefabricated panel needs to be inspected for cracks and damages upon arrival on-site. Before delivery, the prefabricated panels rested for over 28 days, which is known as the curing period. Sometimes cracks might develop during these periods. Damages of the panel also could occur during the transportation process. In addition, the prefabricated wall panel manufacturer usually offers a product warranty, but the warranty is not valid if the panel is damaged over transportation. Therefore, if the panels were painted off-site, the cracks, imperfections or damages would not be visible during the quality inspection.

During the on-site visit, the author has conducted the second round of requirements engineering. In the act of the activity, the functional and non-functional requirements were formulated based on the feedback from interviews and observation. The results reflect a general view of the requirements that industry practitioners consider important.

Functional requirements for OCR collected from the on-site visit are:

- Compatibility: The proposed OCR needs to be compatible with the conventional construction site, method, and skills. It is an incremental process to adopt OCR in a rather conventional industry.
- Mobility: The proposed OCR needs to be lightweight, compact, and agile. This is due to most of the PHC sites are very congested, so the system design can have a huge implication on the system manoeuvrability and practicality.
- Logistics: The proposed OCR needs to be able to deliver by the standard means of transportation, e.g. van, or a lorry.

Non-functional requirements for OCR collected from the on-site visit are:

- Usability: The existing labourers can operate the proposed OCR with minimal training
- Performance: The work that is performed by OCR should at least match the conventional method in terms of speed, quality, and cost.
- Operational: The proposed OCR should be able to operate in most of the site condition, for example, high temperature, humidity, and potentially work overnight.
- Training: It is necessary to establish a training facility that will overlook training, service, and certification aspects of the technology.
- Cultural acceptance: The proposed OCR would be culturally acceptable if it enhances the existing work but not to replaces the worker.
- Health and Safety: The proposed OCR should not impose additional operational or health-related hazards.
- Regulation and legislation: The proposed OCR should comply with the existing regulation; it needs to be approved by the HKHA. Incentives from the authorities will promote the adaptation of innovative products in the construction industry.

3.4.3 Impacts and summary

The on-site visit offers an opportunity to assist the project team to understand the existing PHC site operation, to explore the challenges that practitioners are facing on a daily basis. Based on the response from the on-site interviews and investigation, the PHC sector in Hong Kong has the potential and willingness to implement construction robotics and automation technology. Among the selected tasks, façade work, interior painting, and interior plastering have the higher potential to be automated.

In spite of the positive feedback, there are clear constraints while developing OCR for the PHC sector. First, the conventional construction industry is reluctant to change. The existing regulations could impose negative implications on introducing innovative systems to on-site tasks. For instance, the sub-contractor has to submit a document called the method statement that indicates the method and tools to be adopted for the specific task. Any drastic change to the work method, equipment or material may result in rejection over the tendering process. Second, there is a visible discrepancy of priorities when it comes to which KPI is more important to the specific trade. For example, hoisting and positioning of the prefabricated wall elements would value speed and safety over cost and quality, this is because of the cost and quality for this task will remains constant if the speed and safety of the operation will not be improved. In regards to interior painting, the finishing quality is highly valued over speed. This is due to the preparation of the units; the building inspector must check the quality of the interior finish before handing it over to the residents of the public housing. If it does not reach the expected standard, the building inspector will request the contractor to rework on the insufficient areas. Therefore, to understand the priorities of the specific task is crucial to OCR development. Finally, it is crucial to test and refine the proposed robotic application in a pilot project, in which the biggest challenge is to introduce construction robots into an on-going project without causing any delays.

3.5 Co-creation workshop

Co-creation is a method that engages stakeholders at the beginning of the development stage and aims to tailor the product, or services to the demand and expectations of the customers and end-users. Co-creation activities usually take place in the form of interactive workshops with target groups, and relevant stakeholders, which offers an opportunity to encourage the participants to brainstorm, embrace creativity, exchange experience, and express interests. By carrying out a co-creation workshop, the project team will receive valuable feedback on how the stakeholders and end-user would like to experience the proposed product or services. In the CIC project, the TUM project team would like to encourage the construction practitioners to attend the co-creation workshop in an early stage, in order to increase awareness of the proposed technologies, enhance attachment, embrace engagement of the project, and to ensure the added value is more evident to the customer or the end-user (Potts *et al.*, 2008).

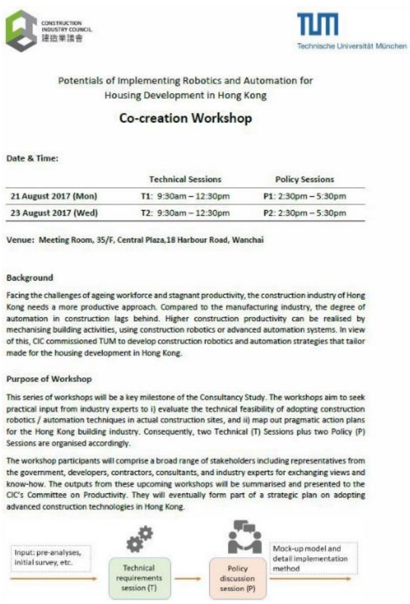
3.5.1 Method

The co-creation workshops will be a key milestone of the consultancy study. The objective of the workshops is to seek practical input from industry experts to i) evaluate the technical feasibility of adopting construction robotics and automation techniques in actual construction sites, and ii) map out pragmatic action plans for the Hong Kong building industry. The facilitator of the workshop was Dr. Thomas Linner, and the co-facilitator was the author. The roles of the facilitator are to lead the participants through the workshop steps, oversee the activities and to encourage round table decisions to stimulate creative thinking, and to offer equal opportunities for each participant to express their own interests (Bφdker, Grφnbæk and Kyng, 1995). The co-facilitator will assist the facilitator in managing the workshop to make sure all relevant material and feedback are documented. Furthermore, to analyse the co-creation workshops results. Approximately 40 experts from industry, academia, government agencies/ authorities, consultants, and NGOs are invited to participate in the workshops. The name of the participants are confidential, yet the affiliations of the participants are as shown in Table 34. The invitation and workshop agenda was distributed to the invited participants in advance, see Figure 27.

Table 34: The co-creation workshop participants and their affiliations.

Type of stakeholders	**Affiliations**
Contactors	Gammon construction, Yau Lee construction, China State construction, ChunWo construction, Hanison construction, Kim Hung construction,
Property developer	Sun Hung Kai Properties, Nan Fung Group, Shui On Group, Swire Properties
Academia	The Hong Kong Polytechnic University (PolyU), HKUST Robotic Institute,
Government agencies/ authorities	Architectural Services Department (Arch SD), HA, Urban Renewal Authority (URA), Development Bureau (DEVB), BD, The Hong Kong Construction Association (HKCA)
Architects	P&T Group, Leigh orange,
Consultants	HKSTP, David SK Au & Associates, Logistics and Supply Chain MultiTech R&D Centre (LSCM), Advisian, Lesk
Client	CIC

The workshops were divided into two sessions: a technical session (T-Session) and a political session (P-Session), see Figure 28.


CONSTRUCTION INDUSTRY COUNCIL 建造業議會

Technische Universität München

Potentials of Implementing Robotics and Automation for Housing Development in Hong Kong

Co-creation Workshop

Date & Time:

	Technical Sessions	**Policy Sessions**
21 August 2017 (Mon)	**T1**: 9:30am – 12:30pm	**P1**: 2:30pm – 5:30pm
23 August 2017 (Wed)	T2: 9:30am – 12:30pm	P2: 2:30pm – 5:30pm

Venue: Meeting Room, 35/F, Central Plaza,18 Harbour Road, Wanchai

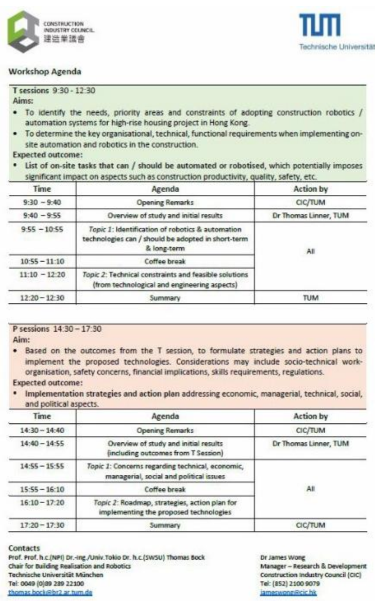
Background

Facing the challenges of ageing workforce and stagnant productivity, the construction industry of Hong Kong needs a more productive approach. Compared to the manufacturing industry, the degree of automation in construction lags behind. Higher construction productivity can be realised by mechanising building activities, using construction robotics or advanced automation systems. In view of this, CIC commissioned TUM to develop construction robotics and automation strategies that tailor made for the housing development in Hong Kong.

Purpose of Workshop

This series of workshops will be a key milestone of the Consultancy Study. The workshops aim to seek practical input from industry experts to i) evaluate the technical feasibility of adopting construction robotics / automation techniques in actual construction sites, and ii) map out pragmatic action plans for the Hong Kong building industry. Consequently, two Technical (T) Sessions plus two Policy (P) Sessions are organised accordingly.

The workshop participants will comprise a broad range of stakeholders including representatives from the government, developers, contractors, consultants, and industry experts for exchanging views and know-how. The outputs from these upcoming workshops will be summarised and presented to the CIC's Committee on Productivity. They will eventually form part of a strategic plan on adopting advanced construction technologies in Hong Kong.


CONSTRUCTION INDUSTRY COUNCIL 建造業議會

Technische Universität

Workshop Agenda

T sessions 9:30 - 12:30

Aims:

- To identify the needs, priority areas and constraints of adopting construction robotics / automation systems for high-rise housing project in Hong Kong.
- To determine the key organisational, technical, functional requirements when implementing on-site automation and robotics in the construction.

Expected outcome:

- List of on-site tasks that can / should be automated or robotised, which potentially imposes significant impact on aspects such as construction productivity, quality, safety, etc.

Time	Agenda	Action by
9:30 – 9:40	Opening Remarks	CIC/TUM
9:40 – 9:55	Overview of study and initial results	Dr Thomas Linner, TUM
9:55 – 10:55	*Topic 1*: Identification of robotics & automation technologies can / should be adopted in short-term & long-term	All
10:55 – 11:10	Coffee break	
11:10 – 12:20	*Topic 2*: Technical constraints and feasible solutions (from technological and engineering aspects)	
12:20 – 12:30	Summary	TUM

P sessions 14:30 – 17:30

Aim:

- Based on the outcomes from the T session, to formulate strategies and action plans to implement the proposed technologies. Considerations may include socio-technical work-organisation, safety concerns, financial implications, skills requirements, regulations.

Expected outcome:

- Implementation strategies and action plan addressing economic, managerial, technical, social, and political aspects.

Time	Agenda	Action by
14:30 – 14:40	Opening Remarks	CIC/TUM
14:40 – 14:55	Overview of study and initial results (including outcomes from T Session)	Dr Thomas Linner, TUM
14:55 – 15:55	*Topic 1*: Concerns regarding technical, economic, managerial, social and political issues	All
15:55 – 16:10	Coffee break	
16:10 – 17:20	*Topic 2*: Roadmap, strategies, action plan for implementing the proposed technologies	
17:20 – 17:30	Summary	CIC/TUM

Contacts

Prof. Prof. h.c.(NPI) Dr.-Ing./Univ.Tokio Dr. h.c.(SWSU) Thomas Bock
Chair for Building Realisation and Robotics
Technische Universität München
Tel: 0049 (0)89 289 22100
thomas.bock@br2.ar.tum.de

Dr James Wong
Manager – Research & Development
Construction Industry Council (CIC)
Tel: (852) 2100 9079
jameswong@cic.hk

Figure 27: An example of the co-creation workshop invitation and agenda.

Each session consists of nearly ten participants, to allow group discussion and group activities. The technical session focused on prioritizing on-site tasks necessary to be automated or robotized. Then, the workshop participants evaluate the identified task in detail, discuss technical constraints and propose feasible solutions. The political session focused on the policy context and summaries of soft requirements of the tasks systems, which were selected in the technical session. Finally, participants discussed how to implement the selected systems, roles of the key stakeholders and the feasible business models.

Figure 28: Snapshots of the co-creation workshop.

Workshop theme: T-session (held on 21 August 2017).

At the beginning of the T-session, the facilitator briefly introduced the progress of the project and the initial research including online survey results to the workshop participants. The outcomes of the on-site case study and primary examples of proposed system designs were briefly introduced. The proposed design includes a façade work robotic system, interior painting robotic system, interior plastering robotic system, and hoist, positioning robotic system.

Topic 1 (T1): identification of robotics & automation technologies that can / should be adopted in short-term & long-term scopes. The data was collected through a round table discussion during this stage.

This session focused on the identification of specific on-site tasks that experience the following challenges:

- Facing a labour shortage
- Low productivity
- Poor construction quality
- High risks

To evaluate whether the identified on-site tasks can be improved by using automation or robotics, the workshop participants were given four stickers and were given a chance to vote on the tasks that they considered as a priority, see Table 35 and Figure 29. The numbers of the stickers were counted afterwards:

Table 35: Priority tasks analysis and the numbers of votes received on day one.

Priority tasks	Received votes
Automated formwork	1
Component positioning	0
Façade works, exterior works	7
Interior plastering	7
Interior painting	10
Welding	3
Rebar work, rebar fixing	3
Systems for inspecting construction quality	2
M&E works, including external building services	3

Astonishingly, the results are identical to the results from the on-site investigation. This further validates that these three tasks have a larger demand to be automated.

Figure 29: The workshop participants are actively engaged in the voting process.

The general requirements for the top-ranked tasks (e.g., façade works & exterior works, exterior works & interior plastering, and interior painting) were identified as follow:

- To consider the relationship of application area/time vs. the setup time for the system on the site. The proposed system needs to be flexible and easy to install in the congested space on-site.
- To consider the movement and logistics of the robots on the site:
- The proposed system needs to be compact, lightweight and easy to manoeuvre.
- To consider the complex geometry of sites, buildings, floorplans, etc.:

  - The proposed system needs to be easy to adapt to the different designs of the building.
  - The use of sensors instead of temporary rails: the proposed system should avoid using temporary fixtures that will increase installation time.
- Semi-automatic approach: the proposed system should consider human-robot interaction. The robotic system may not replace on-site labour but should work together with labour to enhance overall productivity. Ultimately, a group of robots might be supervised by only one worker.

Topic 2 (T1): Technical constraints, feasible solutions and detailing selected task areas.
This session focused on detailing the top-ranked tasks by formulating working sequences and summarizing the specific requirements for each task.

a) Façade works, exterior works:

Sub-tasks and work sequences are listed below:

1) Installation of the Gondolas
2) Cleaning and preparation of the external wall, skim coating
3) Apply exterior paint (Primer, Texture and 2 coats of Top coating – usually all layers spray paint, sometimes apply 3rd layer or corners with rollers)
4) Insertion/assembly of exterior piping
5) Inspecting façade paint quality (paint inspection, window-water leakage test, etc.)
6) Dismantling of the Gondolas

Specific requirements:

- Quality of the finish paint is highly important
- Minimize safety risks when operating the system
- Minimize distraction of other tasks (e.g. sometimes up to 80 gondolas work in parallel on one site)
- Selective automation approach (e.g. robot paints large surfaces and human worker paint corners and areas, which are difficult to access for a robot).
- Various design approaches shall be analysed both with and without installation rails that are theoretically possible, according to the architect, if housing authority demands and sets requirement, accordingly.

b) Interior painting, plastering:

Sub-tasks and work sequences:

1) Plastering, repairing of the concrete wall (3-4 months before painting)
2) Cleaning and surface preparation
3) Material supply
4) Painting: coating layer 1 and coating layer 2

Specific requirements:

- Minimize set-up time
- No additional works required would be ideal (fully autonomous system)
- The fully automated and not partially manipulated system is preferred
- Noise proof so it can be used during overnight shifts
- Improve safety on the site
- Increase speed may not be crucial
- Maintaining high quality is important

Workshop theme: P-session (held on 21 August 2017).

Same as in the previous T-session, the progress of the project was briefly introduced by the facilitator and the initial research including online survey results was shared with the workshop participants. The outcomes of the on-site case study and primary examples of the proposed system designs were briefly introduced as well as the preliminary results from T-sessions.

The various concerns and opportunities imposed by implementing the proposed systems were examined. Guidance and potential approaches were discussed in terms of how to address economic, managerial, social and political issues when introducing automation or robotics into the construction industry. Discussion around the business model topic was conducted, which aimed at supporting future implementation in the specific construction phase.

Topic 1 (P1): Concerns regarding technical, economic, managerial, social and political issues. Key non-functional requirements for the highest-ranked tasks that were selected from the T-session are listed below:

- Regulations to accommodate and motivate the implementation of automation and robotics
- Policy encouragement through the local authorities
- Work organization on-site need to be adaptable with the proposed system
- Ergonomics, human-system interface
- Training for prospective workforce
- Create incentives for robot use (e.g., through the bidding process, offered by CIC, BEAM, BIM, etc.)
- Certify the System
- Guarantee high quality of construction
- Guarantee improved safety on the site
- Build up robot supply infrastructure
- Workers-machine balance, upgrading the working environment

- Create attractive new jobs by implementing automation and robotics (i.e., select those tasks and priority areas or develop a selective automation approach that could achieve this goal)
- Consider feasible business models (e.g., 2-3 years payback time is preferred by the potential investor)

Topic 2 (P1): Strategies, action plan and potential business model for the top-ranked tasks that were selected from the T-session. This session focused on issues related to establishing applicable business models for different end-users. Business model components for the top-ranked tasks that were selected from the T-session are listed below:

- A solution is needed for maintaining the robots. This can be achieved by internal training or outsourcing
- Beware of setting up the right degree of complexity for the robot (e.g. a more complex robot will be more autonomous, but will require a high investment and higher skills and maintenance cost, etc.)
- Initial cost & investment: 2-3 years payback time is favourable
- Consider the frequency of use to avoid system redundancy
- Consider the supply chain relationship between the developer, contractor and sub-contractor, etc.
- Identify the orchestrator - The developer or the contractor. The experiences shared in the tunnel boring machine (TBM) distribution might offer valuable insight

Workshop theme: The second T-session (held on 24 August 2017).

Topic 1 (T2): Identification of robotics & automation technologies that can or should be adopted in short-term & long-term. The identified priority tasks can be seen in Table 36:

Table 36: Priority tasks analysis and the numbers of votes received on day two.

Priority tasks	**Received votes**
Automatic formwork, including compaction of concrete, man access, 3d printing of formwork	5
Hoist and positioning in combination with prefabricated elements	7
Exterior façade works, including painting, piping, cleaning	4
Interior plastering	0
Interior painting	1
Work-related to reinforcement works on the site	0
Foundation works	0
Water leakage testing (for each window after completion of building exterior)	0
Compaction of concrete	0
Automated horizontal/vertical welding of prefabricated components connections on the site	5
Drilling works	0
Stone finishes	0
Quality control	0
Line marking	0
Construction progress monitoring	0

Logistics on the site	1
M & E works in the lift shafts	0
Tower crane operations	6

After this round of voting, we have noticed the results are different from the first T-session. This may be influenced by the composition of the participant. The general requirements for the top-ranked tasks e.g., Hoist and positioning in combination with prefabricated elements, tower crane operations, automatic formwork, and automated welding were identified as follow:

- To consider the compatibility of platform technologies between various robot applications: e.g. BIM, Virtual reality (VR), sensors onboard, global sensors such as drones for sensing and inspection, etc.
- To consider that some repetitive tasks can be solved by a machine learning approach (i.e., the robot learns from application to application)

Topic 2 (T2): Technical constraints, feasible solutions and detailing selected task areas. This session focused on detailing the top-ranked tasks by formulating working sequences, analysis constraints, and summarizing the specific requirements for each task.

a) Hoist and positioning & tower crane:

Sub-tasks and working sequences:

1) Hooking (end-effector, automated, etc.)
2) Installation, climbing task
3) Ground logistics and crane feeding, automate temporary loading bucket on the ground
4) Logistics to the site/ JIT
5) On-site task decision support module
6) Banks man’s collaborative work while hoisting
7) Containing and reducing over-sailing

Specific requirements:

- Control mode / Human-computer interaction (HCI)
- To consider platform technologies. Different ranges, specifications of systems based on a common platform design. This will ease system upgrading and manufacturing
- Minimize the impact of the on-site construction cycle
- Provide ICT support with decision making and scheduling
- To ensure the usability aspect of the proposed system. The system is easy to operate by the existing workforce
- Increase safety on the site
- Increase productivity on the site (reduction of labour, increase speed, e.g., through faster hoisting procedure, etc.)

b) Automatic formwork:

Sub-tasks and working sequences:

1) Worker access & to facilitates cooperation between various trades
2) Concrete compaction
3) Rising/climbing
4) Dismantling
5) Smart form (e.g., integrated quality inspection, concrete temperature measurement and control, etc.)
6) Support with organization and scheduling.

Specific requirements:

- Control mode/Human-computer interaction (HCI)
- Consider platform technologies
- The main obstacle: cost
- The government needs to guarantee robot quality, safety, etc. through certification, regulation and training.
- Consider minimal margins of 3% in public housing
- Systematization and modularization of smart formwork needed

c) Automated welding on the site:

Sub-tasks and working sequences:

1) To weld temporary elements
2) To weld permanent elements
3) To gain access on higher floor levels with covered walkways
4) Perhaps move all welding tasks off-site

Specific requirements:

- High mobility/flexibility is needed, maybe propose a “spider-like robot”
- To consider carefully which work can be shifted to an off-site facility
- Overnight or 24/7 operation
- The robot needs to deliver/ensure the structural quality of the welding part and to avoid defects (in particular related to statics)
- Enhance safety on the site
- Changeable end-effectors for different tasks (e.g. the same robot may be used for 3D-printing of formwork)

Workshop theme: The second P-session (held on 24 August 2017).

Topic 1 (P2): Concerns regarding technical, economic, managerial, social and political issues. This session focused on the analysis of the key business model for the top-ranked tasks that were selected from the P-session, which are listed as below:

- To define the degree of prefabrication and to determine the remaining tasks that robots should focus on
- How to combine the use of robotic and BIM and to favour smaller companies
- To consider fierce completion among contractors and small margins in the public housing
- Robotics may require a change in the whole ecosystem; to establish a new industrial network
- Due to confined site space, robots need to be very flexible and mobile
- To create incentives and minimize the risks for companies that might be willing to adopt the approach (e.g. through cheap loans from the bank or other funding parties)
- To consider the robot application as early as possible in the design process. It is necessary to consider adopting ROD concept during the development stage
- Starting with low-risk, simple tasks, then move onto more complex tasks
- It is highly recommended to evaluate performance through pilot projects
- To certify the performance of robots or automated systems
- To analyse TBM adoption and to extract experiences from it

Topic 2 (P2): Strategies, action plan and road map draft. Base on the feedback from the previous sessions, the workshop participants had an opportunity to discuss how to implement selected applications strategically, and to draft the initial roadmap. The development phases were identified as below:

- Phase 1: Task identification
- Phase 2: Detailed design and final selection of the mock-up based on a selected system
- Phase 3: To adopt a modular design approach for various systems. To identify robot supply infrastructure
- Phase 4: 1:1 scale prototype(s)
- Phase 5: To conduct pilot projects
- Phase 6: Robot performance certification and system setup
- Phase 7: Training and government policy measures (develop a strategy for industry incentives, to minimize risks, dissemination, etc.)
- Phase 8: Implement robot supply infrastructure and to implement strategies for introducing incentives, risk minimization
- Phase 9: To introduce a plug-and-play design approach and to implement robots on-site

3.5.2 Outcomes

The workshops along with the survey and on-site case study provide extensive insight, which indicates how the construction industry in Hong Kong rationalizes the implementation of automation and robotics on-site. A number of tasks were considered to have the potential to be improved considerably by automation and robotic technologies. Based on these results, a system key performance analysis is conducted to identify the priority areas for the project. The key performance of the selected system includes safety, labour shortage, improvement of quality, adaptable, compact and flexible design, acceptance, and improvement of productivity.

The spider chart is used as a metric to demonstrate a dynamic trend of the influential key performance, and each one is rated from low to high variables. For example, in this case, five points indicate a better performance score than four points. There were five finalists chosen for the evaluation, which include façade work and exterior work system, interior painting, plastering system, hoist and positioning system, automatic formwork, and automated welding system. Each system will receive a score based on the assigned performance criteria. The performance criteria or KPIs can be described as below, see Table 37:

Table 37: The description of the KPIs for the spider charts.

KPIs	Description
Safety	The system will improve operational safety and reduce health and safety hazards
Labour shortage	The system will fill the labour shortage gaps in the existing market condition
Improvement of quality	The system will improve the working process and the final quality of the specific task
Adoptable, compact and flexible design	the system is flexible and can be easily adapted to the existing construction industry
Acceptance:	The system is in favour of the construction industry. The finalized system can be implemented relatively straightforward without causing additional complications
Improvement of productivity	The system will evidently improve the productivity of the specific task, and speed up the entire working process

The spider chart below demonstrates the key performance scores of the façade work & exterior work system, see Figure 30.

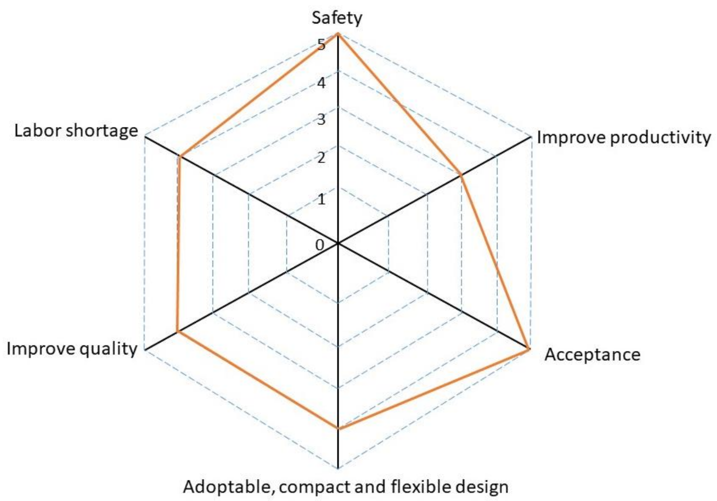


Figure 30: Spider chart showing the key performance scores of the façade work & exterior work system.

- Safety (scored 5): The majority of the façade or exterior tasks can impose a high risk for the worker. The proposed system can improve operational safety significantly

- Labour shortage (scored 4): Façade or exterior task experiences labour shortage, and a worker has to receive special training to operate the suspended working platform
- Improvement of quality (scored 4): To remain the high standard of quality is very important and the system can improve the working process and the final quality
- Adoptable, compact and flexible design (scored 4): The system can be designed by using a platform strategy to achieve high flexibility
- Acceptance (scored 5): The system was popular among the participants during the workshop, and the on-site visit. There were no obvious objections to the concept
- Improvement of productivity (3): The system needs to be tested through a pilot project to validate this hypothesis

The spider chart below demonstrates the key performance scores of the interior painting, plastering system, see Figure 31.

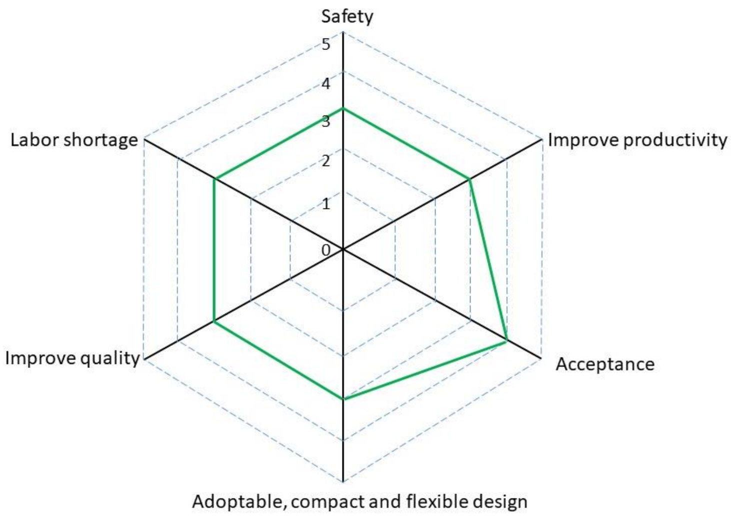


Figure 31: Spider chart showing the ky performance scores of the interior painting, plastering system.

- Safety (scored 3): The current work is carried out under a relatively safe environment
- Labour shortage (scored 3): The current labour market can cope with the market demand
- Improvement of quality (scored 3): The current quality is reasonably high, which was achieved by skilled labour. The system needs to be tested through a pilot project to prove this hypothesis.
- Adoptable, compact and flexible design (scored 3): The system needs to be highly adaptable to allow the system to be implemented in different floor layouts. It is challenging to achieve this under the current site conditions
- Acceptance (scored 4): The system was recommended during the workshop.
- Improvement of productivity (3): The systems need to be tested through a pilot project to prove this hypothesis

The spider chart below demonstrates the key performance scores of the hoist and positioning & tower crane system, see Figure 32.

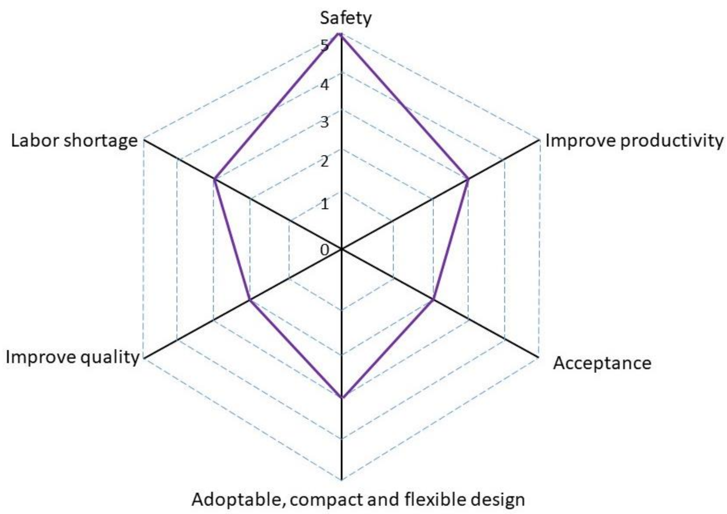


Figure 32: Spider chart showing the key performance scores of the hoist and positioning & tower crane system.

- Safety (scored 5): The current work is very risky; there are many concerns under the hoisting and crane safety, e.g. material falling, overloading, human error. Therefore, the proposed system can improve hoisting and crane safety
- Labour shortage (scored 3): The current labour market can cope with the market demand, although the labour cost is very high for the crane operator
- Improvement of quality (scored 2): The system needs to be tested through a pilot project to prove this hypothesis
- Adoptable, compact and flexible design (scored 3): It is challenging to modify or upgrade hoisting and crane systems. The existing systems need to be certified by the industry authority
- Acceptance (scored 2): The system was recommended during the workshop. However, it is extremely time-consuming and risky to use it for a pilot project. Additionally, if the system testing is only done under a lab environment, the results might be less comprehensive
- Improvement of productivity (3): The system needs to be tested through a pilot project to prove this hypothesis

The spider chart below demonstrates the key performance scores of the automatic formwork system, see Figure 33.

- Safety (scored 5): The current operation is very risky, and there are many concerns regarding formwork erection and dismounting. So, the proposed system can improve operation safety

- Labour shortage (scored 3): The current labour market can cope with the market demand, although the labour cost is very high for the crane operator
- Improvement of quality (scored 4): self-climbing formwork provides an example that the proposed system can further improve the working process as a whole
- Adoptable, compact and flexible design (scored 5): The existing self-climbing formwork systems are designed to be very flexible. The proposed system will take this feature as a reference
- Acceptance (scored 2): The system was recommended during the workshop. However, it is extremely time-consuming and risky to use it for a pilot project. Additionally, if the system testing is only done under a lab environment, the results might be less comprehensive
- Improvement of productivity (4): Self-climbing formwork provides an example to illustrate the proposed system can potentially improve productivity

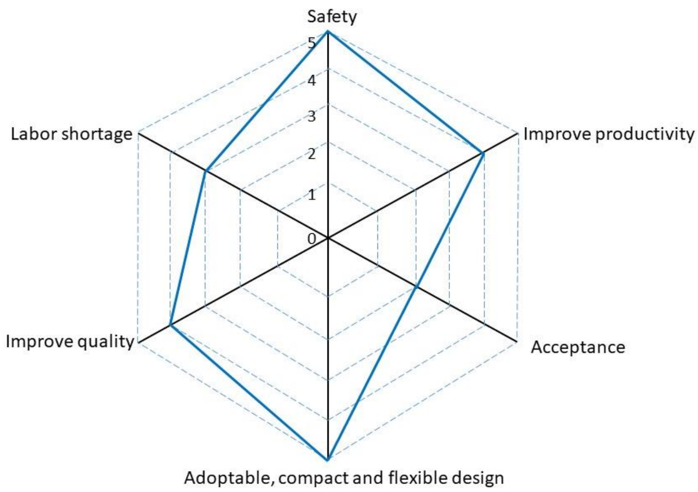


Figure 33: Spider chart showing the key performance scores of the automatic formwork system.

The spider chart below demonstrates the key performance scores of the automated welding on-site, see Figure 34.

- Safety (scored 4): The current work is very risky Especially health hazards and personal injury in the proposed system can improve operation safety drastically
- Labour shortage (scored 5): This task experiences high labour shortage, and the worker has to receive special training to be able to work on-site. The labour cost for the welder is high
- Improvement of quality (scored 5): Many other industries rely on welding robots to improve welding quality. This may show a similar trend in the construction industry
- Adoptable, compact and flexible design (scored 4): Welding systems can be designed to be highly flexible and versatile, thus capable of different welding applications
- Acceptance (scored 3): The system was recommended during the workshop. However, it is extremely time-consuming and risky to use for a pilot project. Additionally, if the

system testing is only done under a lab environment, the results might be less comprehensive

- Improvement of productivity (scored 3): The system needs to be tested through a pilot project to prove this hypothesis

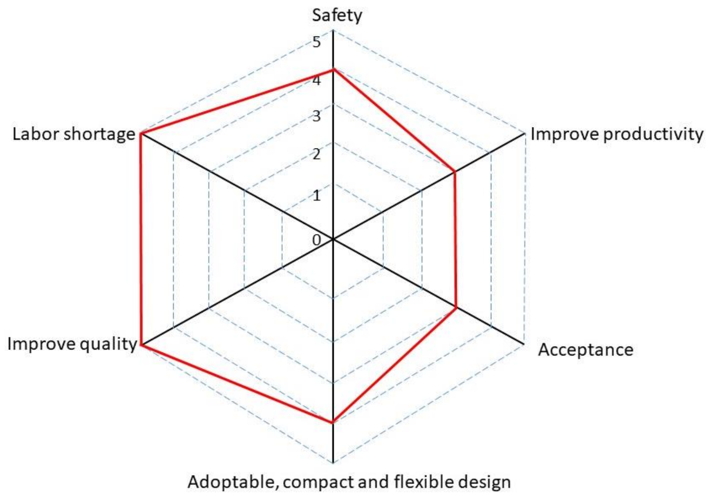


Figure 34: Spider chart showing the key performance scores of automated on-site welding.

Key insight: the superimposed spider chart below demonstrates a dynamic trend of the influential key performance that were scored by each individual system, see Figure 35.

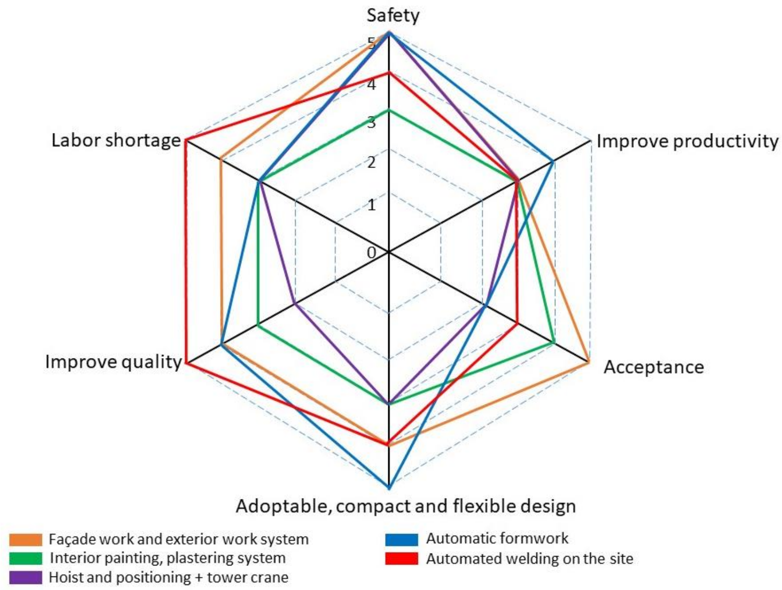


Figure 35: Summative spider chart showing a dynamic trend of the influential key performance that scored by each individual system.

- Safety has been identified as one of the most critical criteria for façade and exterior work system, automatic formwork and hoist system, positioning & tower crane
- Adoptable, compact and flexible design has been identified as the second most dominant measure. This was also pointed out by participants a few times over the workshop; the proposed system has to be adaptable to the changes of the on-site environment, building layouts and design features
- The proposed system needs to address the increasing trend of labour shortage and to improve finishing quality as well as productivity
- In general, based on the acceptance scores, the construction industry is open to implementing automation and robotics
- To convince the stakeholders to willingly adopt automation and robotics on-site, we have to carry out a compelling pilot project with attractive incentives, which requires help from the government

In summary, the façade work and exterior work system received a total score of 25; the interior painting and plastering system received a total score of 19; the hoist and positioning system received a total score of 18; the automatic formwork received a total score of 23, and automated welding system received a total score of 24. Therefore, taking the budget and time into consideration, the TUM project team (facilitator and co-facilitator) together with the workshop participants decided to choose the façade work and exterior work system as the priority in this project.

3.5.3 Impacts and summary of the requirement

The workshops offered a unique opportunity that brings a broad range of stakeholders from the construction industry together to discuss and exchange views and to share the outcomes from the initial study, on-line survey and on-site case study. The outputs from this upcoming workshop will become the principle guidance that supports the project aims, to narrow down the priority areas, and to map out strategies for implementing construction robotics or advanced automation systems in Hong Kong.

The data collected from the online survey, on-site visit, and the co-creation workshops are qualitative, yet convincingly informative, which provide an extensive insight that indicates how the construction industry in Hong Kong rationalizes the implementation of automation and robotics on-site. In general, the responses from the industry, academia, and government agencies are positive. Four key challenges faced by the construction industry were identified, which include labour shortage, low productivity, poor construction quality, and high risks on-site. The T-session of the workshop identified on-site tasks that can be potentially improved by implementing automation and robotics. The T-sessions also detailed the top-ranked tasks by formulating their working sequences, sub-tasks and summarizing the subsequent requirements. The P-sessions were dedicated to discussing economic, managerial, social and political issues when introducing automation or robotics on-site. The discussion was conducted in accordance with the experience and expertise of the participants. A systemic approach that reviewed the strategies may be applicable when engaging key stakeholders in addition to how to conduct final implementation in a later stage. Last, but not least, several different types of business model propositions were examined and the system for the next phase was proposed.

Besides that, the author has identified some minor issues that need to be addressed during the next development stage. The requirements collected through co-creation workshop indicate that the Hong Kong PHC sector is confident in adopting automation and robotic technologies, however, the expectation is ostentatious, or the sector underestimates the challenges of developing a practical OCR. For example, some participant suggested that the robot needs to be fully autonomous and outperform its human counterpart, yet minimize development cycle and costs. This may sound like a reasonable request under normal circumstances, however, in terms of OCR development, there are very limited references that can be directly copied from the other sectors. Due to the special circumstances of the construction task. Not many parts, components, and software application can be integrated with the proposed OCR straightaway even from the most closely related sectors, such as industrial robotics sector. Even though sourcing off-the-shelf parts and components can reduce development time and cost significantly, however, in this case, many parts and components have to be modified and re-engineered. This is because the products on the existing market are not designed to serve the purposes that the proposed OCR is going to accomplish. Some participants also suggested if the robot is semi-autonomous, then human-robot Integration or assignment of the labour and robot to the functions is one of the key elements that need to be considered throughout the design stage. In addition, at the end of the co-creation workshop, encouraged by the feedback from the industry practitioners, CIC requested TUM project team to carry out the detailed design of the façade work and exterior work system and to build a demonstration mock-up as a simulator that would demonstrate the OCR concept to the construction industry. One of the main reasons why CIC decided to further develop the façade finishing system is that this is the only system that can be tested in a pilot project on-site. It is too risky to test other systems, particularly those can potentially cause a delay due to system failure while conducting the on-site pilot testing. The detailed design process will be described in the following section.

3.6 Initial system design

Based on the key findings from the previous stages, namely initial research, online survey, on-site case study, and co-creation workshops, this section will focus on the development of the multifunctional façade finishing robot. A systematic design method will be developed based on the case study results. It is not a universal approach, nevertheless, the approach provides an analytical method that will assist OCR designers to understand the levels of autonomy discrepancies in practical applications, and to formulate the optimum level of automation, as well as to identify the trade-offs between automation levels and human factors in the specific façade task. In addition, even if the designer does not possess previous experience of developing OCR, the proposed design method can be used as an informative guideline for a similar project.

3.6.1 The allocation of function and level of automation

OCR systems are either fully autonomous or semi-autonomous, which are controlled or operated by complexed robotic programs and sophisticated hardware integration. However, due to the complexity of the construction tasks, OCR cannot completely replace human labour in many aspects. Despite the advances in ML or deep learning, OCR is not able to make judgments or decisions by using self-initiatives. OCR is unable to deal with unexpected situations or proactively react in an emergency. Although, some of these features can be solved technically, the system still would be economically unfeasible. Inappropriate allocation of function between robot and human can create more issues rather than solving the existing challenges. Allocation of function can influence OCR's usability, functionality, therefore, in the early design stage, it is essential to consider which task should be assigned to robot or human.

Many function allocation methods were proposed by researchers over the years, in which the "List approach" by (Fitts, 1951), HEFAM by (Connelly and Willis, 1968), SAINT by (Wortman, Steven D and Deborah J, 1975), and the Price-Tabachnik Descriptive Procedural Model by (Price and Tabachnik, 1968) are the most influential. The proposed approach will be based on the Price-Tabachnik Descriptive Procedural Model. In general, the method is an iterative process that needs to be repeated in various decision-making stages. The method involves the following eight stages, see Figure 36.

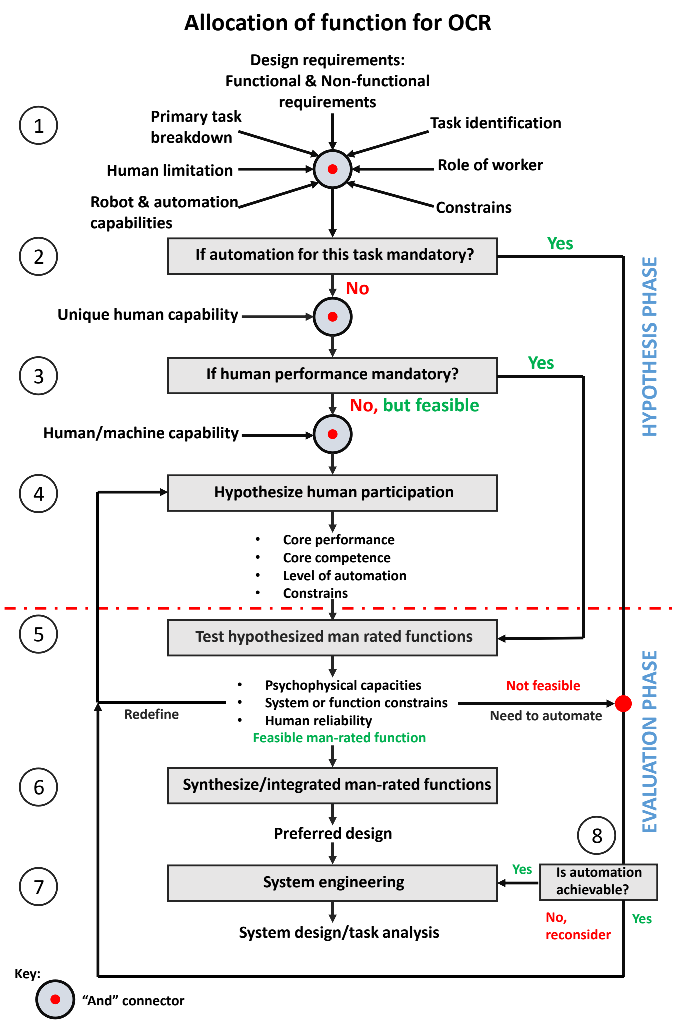


Figure 36: Allocation of function for OCR, based on (Price and Tabachnick, 1968).

The first stage is to conduct detailed task identification and analysis. To understand the work sequence, motion, decision, tools, skills, and organizational structure required to conduct the task in a conventional manner. The second stage is to evaluate if the task must be made to automation, due to the reason of law, regulatory requirement or the task will position the human worker in a hazardous situation. If the task must be automated, then the task will be advancing to stage eight, which is to define whether automation is achievable. If it is not mandatory, the task will be to examine human capability based on various evaluating criteria. Stages one to three will be repeated at the system level, then narrow down to task level, then sub-task level, until the task is clearly allocated to either human or OCR. The third stage is to define whether or not OCR can carry out the task, or whether to assign the work to human is mandatory. If it is mandatory, the task will advance to stage five. If it is not, but feasible, then the task will proceed to stage four. Stage four will be focusing on investigating the feasibility of conduct the task either by human labour or by OCR. Stage five will exam the hypothesized man-rated functions, to evaluate the psychophysical, constraints, and reliability aspects of the task. If it is feasible, then as part of stage six, the human function will be studied and it will be decided whether the operator is well suited to complete the function, or how to enhance human capability at the job by offering adequate support, instead of using automation. When the man-rated functions are characterized as not feasible, as part of stage eight, the task should be considered to be automated, if it is feasible to be automated then the task will move to stage seven, which is to start system engineering. Otherwise, the flow of the task will go back to hypothesize human-rated functions and seek an alternative method that does not require automating the task. Since the decision was made to develop a multifunctional façade finishing robot, the author will take the exterior painting task as an example to demonstrate how to perform the allocation of function for OCR. The method can also be adopted for other construction tasks.

The exterior painting task can be divided into three task groups, which include the preparation task, execution task, and residual task, see Table 38. During primary work breakdown stage, the subtasks that are associated with the main task will be identified and evaluate what role humans play in the task, what is the limitation faced by a human worker, and constraints, see Table 39.

Table 38: The three task groups of the external painting task.

Exterior painting task		
Preparation task	Execution task	Residual task
Installation of the gondolas	Skim coating	Inspection
Cleaning, preparation of the wall	Primer coating	Dismantling the Gondolas
Setting up materials, tools and equipment	Texture coating	
	Top coating	

Table 39: Task breakdown of the preparation, execution, and residual task.

Preparation task: Installation of the Gondolas, see Figure 37			
Subtasks	**Role of worker**	**Human limitation**	**Constrains**

Install the parapet wall clamps	Decision making, follow instructions, communication, reporting, coordination, physical work	Human errors, the inconsistency of physical strength, misjudge, emotional level	Physical strength, Level of training, Insubordination, low motivation, Mental health
Check docking station	Decision making, observation, reporting, communication	Same as above	
Install the trolley	Decision making, follow instructions, communication, reporting, coordination, physical work		
Safety check	Decision making, observation, reporting, communication		
Installation of the Gondolas, to ask if:			
The task involves sensing	Human-level sensing, cognitive, vision, coordination, hearing		
The task involves interpreting	Yes, the operator needs to follow instructions		
The task involves information processing	Indirect, the information will be passed on to the survivor		
The task involves information storage	Yes, the information will be kept as a written record		
The task involves decision-making	Yes		
The task involves controlling	Yes, to operate the climber, emergency stop device		
The task involves monitoring	Yes		
The task is repetitive	No, it is a one-off task		
The task is dangerous	There are some safety-related hazards		
The task is a high cost	No		
The task involves vocational skills	Yes		
Preparation task: Cleaning, preparation of the wall			
Subtasks	**Role of worker**	**Human limitation**	**Constrains**
Operates the gondola	Decision making, follow instructions, communication, reporting, coordination, physical work	Human errors, the inconsistency of physical strength, misjudge, emotional level	Physical strength, Level of training, low motivation, Mental health
Check the wall surface	Same as above		
Grinding, levelling			
Quality check			
Cleaning, preparation of the wall, to ask if:			
The task involves sensing	Human-level sensing, cognitive, vision, coordination, hearing		
The task involves interpreting	Yes, the operator needs to follow instructions		
The task involves information processing	Indirect, the information will be passed on to the survivor		
The task involves information storage	Yes, the information will be kept as a written record		
The task involves decision-making	Yes		
The task involves controlling	Yes, to operate the climber, emergency stop device, and hand tools		
The task involves monitoring	Yes		
The task is repetitive	Yes, brushing and grinding, chiselling		
The task is dangerous	There are high levels of safety hazards		
The task is a high cost	Yes		
The task involves vocational skills	Yes		
Preparation task: Setting up materials, tools and equipment			
Subtasks	**Role of worker**	**Human limitation**	**Constrains**

<table>
<tr><td>Moving, carrying materials, tools</td><td>Decision making, follow instructions, communication, coordination, physical work</td><td>Inconsistency of physical strength, misjudge, emotional level</td><td>Physical strength, Level of training, low motivation, Mental health</td></tr>
<tr><td>Setting up equipment</td><td colspan="3">Same as above</td></tr>
<tr><td colspan="4">Setting up materials, tools and equipment, to ask if:</td></tr>
<tr><td colspan="2">The task involves sensing</td><td colspan="2">Human-level sensing, cognitive, vision, coordination, hearing</td></tr>
<tr><td colspan="2">The task involves interpreting</td><td colspan="2">Yes, the operator needs to follow instructions</td></tr>
<tr><td colspan="2">The task involves information processing</td><td colspan="2">Indirect</td></tr>
<tr><td colspan="2">The task involves information storage</td><td colspan="2">Yes, very limited, verbal communication</td></tr>
<tr><td colspan="2">The task involves decision-making</td><td colspan="2">Yes</td></tr>
<tr><td colspan="2">The task involves controlling</td><td colspan="2">Yes, need to control airless paint compressor</td></tr>
<tr><td colspan="2">The task involves monitoring</td><td colspan="2">Yes</td></tr>
<tr><td colspan="2">The task is repetitive</td><td colspan="2">Yes, for every floor</td></tr>
<tr><td colspan="2">The task is dangerous</td><td colspan="2">Very low</td></tr>
<tr><td colspan="2">The task is a high cost</td><td colspan="2">No</td></tr>
<tr><td colspan="2">The task involves vocational skills</td><td colspan="2">Yes</td></tr>
<tr><td colspan="4">Execution task: Skim coating, primer coating, texture coating, top coating</td></tr>
<tr><td>Subtasks</td><td>Role of worker</td><td>Human limitation</td><td>Constrains</td></tr>
<tr><td>Skim coating, Painting, cleaning</td><td>Decision making, follow instructions, communication, coordination, physical work</td><td>Inconsistency of physical strength, body posture, misjudge, emotional level</td><td>Physical strength, Level of training, low motivation, Mental health</td></tr>
<tr><td>Refill the paint</td><td colspan="3" rowspan="2">Same as above</td></tr>
<tr><td>Setting up equipment (airless compressor</td></tr>
<tr><td colspan="4">Setting up materials, tools and equipment, to ask if:</td></tr>
<tr><td colspan="2">The task involves sensing</td><td colspan="2">Human-level sensing, cognitive, vision, coordination, hearing</td></tr>
<tr><td colspan="2">The task involves interpreting</td><td colspan="2">Yes, the operator needs to follow instructions</td></tr>
<tr><td colspan="2">The task involves information processing</td><td colspan="2">Indirect</td></tr>
<tr><td colspan="2">The task involves information storage</td><td colspan="2">Yes, very limited, verbal communication</td></tr>
<tr><td colspan="2">The task involves decision-making</td><td colspan="2">Yes</td></tr>
<tr><td colspan="2">The task involves controlling</td><td colspan="2">Yes, need to control gondola, airless paint gun and compressor</td></tr>
<tr><td colspan="2">The task involves monitoring</td><td colspan="2">Yes</td></tr>
<tr><td colspan="2">The task is repetitive</td><td colspan="2">Yes</td></tr>
<tr><td colspan="2">The task is dangerous</td><td colspan="2">There are high levels of safety hazards</td></tr>
<tr><td colspan="2">The task is a high cost</td><td colspan="2">Yes</td></tr>
<tr><td colspan="2">The task involves vocational skills</td><td colspan="2">Yes</td></tr>
</table>

The residual tasks will not be discussed in this case, because the Hong Kong Building Department (HKBD) will carry out the inspection task, and dismantling of the gondola is the same as the installation of the gondolas, which have been described earlier.

The investigation indicates that cleaning, preparation of the wall, skim coating and applying the three layers of paint coats impose higher safety risks, as well as being repetitive and costly. The next step is to investigate these tasks further and to decide whether or not implementing OCR can enhance the current operation. These tasks are also not mandatory to apply automation or manual operation. Thus, it is important to evaluate the unique capability of human and robot, to hypothesize human participation, and man-rated functions. By doing so, the development scopes will be narrowed down, and the tasks to automate will be selected.

Figure 37: Gondola components and installation.

In relation to cleaning, wall preparation task, the unique human capability is that human is able to visually identify the areas of the surface in need of cleaning. Based on the previous experience, humans can coordinate the grinding action, and ensure the correct thickness of the excessive layer of the wall is to be removed. OCR can potentially enhance the grinding motion, due to repetitiveness of motion. The core performance, competence, and constraints of the human in this task can be described as below, see Table 40.

Table 40: The human core performance, competence, and constraints of the preparation task.

Preparation task: Cleaning, preparation of the wall	
Human core performance	• To identify obstacles, defects, and excessive part of the wall • To select and use the correct hand tool for the task • To carry out the task according to the need, based on either previous experience or training • To correct any mistakes • To complete the task according to schedule and budget
Human core competence	• To visually identify different features of imperfections • To identify the wall condition by touching, stroking, tapping • To use the hand tools with adequate motion, precision, and force for the specific task • To observe the finished job, and to identify the finishing quality • To be able to react to an emergency situation • To be able to command self-initiative to learn from each task, and reminder what has been done either correctly or incorrectly
Human constraints	• Wrong judgement • Inconsistency of physical strength • Need to be protected from the external elements, e.g. weather or dust • Exposed to high risks of falling

The next step is to validate the man-rated functions, by looking into three aspects, which include psychophysical capacities, system or function constraints, and human reliability, see Table 41.

Table 41: The psychophysical capacities, system or function constraints, and human reliability of the preparation task.

Preparation task: Cleaning, preparation of the wall	
Human psychophysical capacities	• Can work under pressure • Can work as a team • Can report or alert to the supervisor in case of emergency • Interactive and physically flexible • Can learn from the mistakes • Perseverance and dedication • Professionalism
System or function constraints	• High cost • The complexity of system integration • Low reliability • Imposes additional operational hazards
Human reliability	• Physically incapable after long hours of working • Inadequate level of training • Inconsistency of work ethic and quality • Unpredictable stress level • Suffering from discomfort due to weather or external forces • Health and safety vulnerability

In general, the results indicate that a human is fully capable of doing those tasks, in fact, the human is superior to OCR in terms of observation, flexibility, reaction time in an emergency situation, and decision making. However, there is still room for improvement, such as safety, and quality consistency. Alternatively, the choice of automation should prioritize how to improve operational safety and maintain a high standard of quality.

Concerning the application of the skim coating, primer coating, texture coating, and top coating, the unique human capability is to select the optimum sprayer, nozzle tip size for various coating materials. Skilled human labour is able to make sure paint is distributed evenly on the surface under the suitable operational weather conditions, and to differentiate the finishing quality. OCR can improve the painting process, due to the motion required to perform the task being highly repetitive, and a human is exposed to the element, as well as experiencing the risk of inhaling the fine paint particles. The core performance, competence, and constraints of the human in this task can be described as below, see Table 42.

Table 42: The human core performance, competence, and constraints of the execution task.

Execution task: Skim coating, primer coating, texture coating, top coating	
Human core performance	• To use the airless sprayer system • To cover the wall surface with an even amount of paint • To perform the task safely • To fill up materials • To work as a team (Minimum 2 people) • To conduct initial quality check prior to the HKBD inspection • To complete the task according to schedule and budget

Human core competence	• To identify worn spray gun tip • To adjust the pressure for spraying • To aim the spray gun at a correct distance and position • To operate the spray gun at an appropriate speed • To trigger the spray gun follow a correct timing • Enabled to conduct overlapping technique • Enabled to paint narrow spaces, e.g. inside a corner • Enabled to control the thickness of the coating • To maintain the airless sprayer system regularly • To fill up the paint tank when necessary
Human constraints	• Wrong judgement • Inconsistency of physical strength • Inconsistency of work ethic and quality • Need to be protected from the external elements, e.g. weather or dust • Exposed to high risks of falling

The man-rated functions for the execution task are similar to what has been described earlier for the preparation task. After the investigation, it appears that human can outperform OCR in many related tasks. Yet, some activities still exceed human limitations and in conjunction with the unique Hong Kong circumstance such as labour shortage, the ageing workforce, and diminishing productivities. To consider these two aspects together, it is clear that the current Hong Kong situation will intensify the identified human constraints. This is directly associated with the ageing workforce, long working hours, and on-site health and safety aspect (Siu, Phillips and Leung, 2003). Mostly, the two most costly and respective tasks, grinding and spraying, can be enhanced by adopting automation and robotic technologies. The project team decided to focus on the painting function for the first generation OCR, and the grinding function will be developed as conceptual designs and will be iterated in the near future. In the next section, the author will analyse which type and level of automation will be the most appropriate for the proposed system design, as well as assess the technical and implementation feasibility of the concept.

On-site automation can refer to either full or partial replacement of the tasks that used to be performed entirely by humans. Automation does not offer all the solutions to the identified challenges, yet can provide an alternative method that enhances human performance. The system designer needs to be aware of what type of manual activities and information processing belong to the conventional task in order to decide the optimal levels of automation (Parasuraman, Sheridan and Wickens, 2000). The author will first analyse the human action performance, and then investigate the human information processing performance that is affiliated with the exterior painting application. As mentioned previously in the on-site case study, that after the exterior façade is well prepared, three layers of coating will be applied. The team of workers is usually working in a crew of two; one is in charge of spray paint and operating the gondola, here is to refer as sprayer, and the other worker is responsible for filling, mixing, and delivering paint, as well as moving the airless compressor to the current working floor, referred to as assistant, see Figure 38. The assistant will follow the method statement and mix each coating into the correct ratio. The sprayer will carry out the most physically demanding task, which is to apply paint on the building surface.

Despite working at great heights, exposed to the external environment while remaining constant spray pattern and quality of finish, the basic body gesture of the sprayer is standing upright, however, the hosting position of the gondola is extended out as an anti-collision measure that ensures there is sufficient distance between the external wall and the gondola.

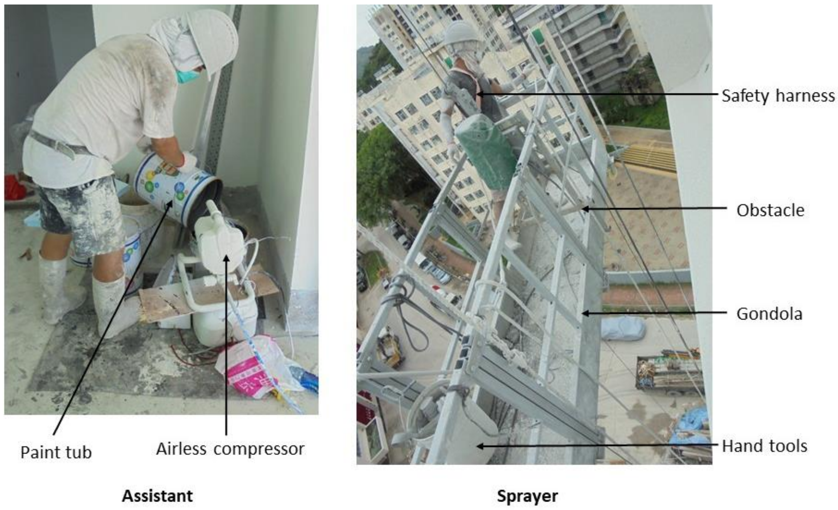


Figure 38: The ground operation of the exterior painting application.

This has imposed some degree of difficulties to the worker when reaching out to the far corner positions of the wall. During the on-site visit, the author kept detailed imagery and video records, which was carefully analysed, see Figure 39. Based on the data, it is noticeable that the spraying task requires extensive upper body movement, in which shoulder, upper arm, forearm, wrist, and fingers that perform the most repetitive motions. The basic hand, arm, back and neck gestures during spraying are pulling, tilting, extending, twisting, swing both horizontally and vertically, bending, and turning. The aforementioned tasks the operator requires experience and vocational training. The occupation is not accretive to the younger generation, due to it being physically demanding, dirty, and potentially dangerous. The sprayer is secured with safety harnesses, covered with protective closing, and a dust mask. On the other hand, the assistant will perform simpler tasks, such as mixing, carrying, lifting, and pouring paints into the tank. Sometimes the assistant will adjust the pressure setting on the airless compressor according to the sprayer's command. This exercise helps the system designer to figure out the motions required for the spraying task, which is extremely useful when deciding the mechanical moments required for the OCR. To a certain degree, this analysis lays the foundation of kinematics development for the proposed OCR.

Spray painting the exterior wall may not sound very complex, yet it consists of all four information processing activities. To the human, these activities are standard, which the skilled worker has been trained to receive, process, and make the decision based on gathered information. However, the method that OCR collects and processes information is different from that of a human, especially when dealing with intertwining information. In general, the human information processing activity can be divided into four stages including information acquisition, information analysis, decision selection, and action implementation (Parasuraman, Sheridan and Wickens, 2000).

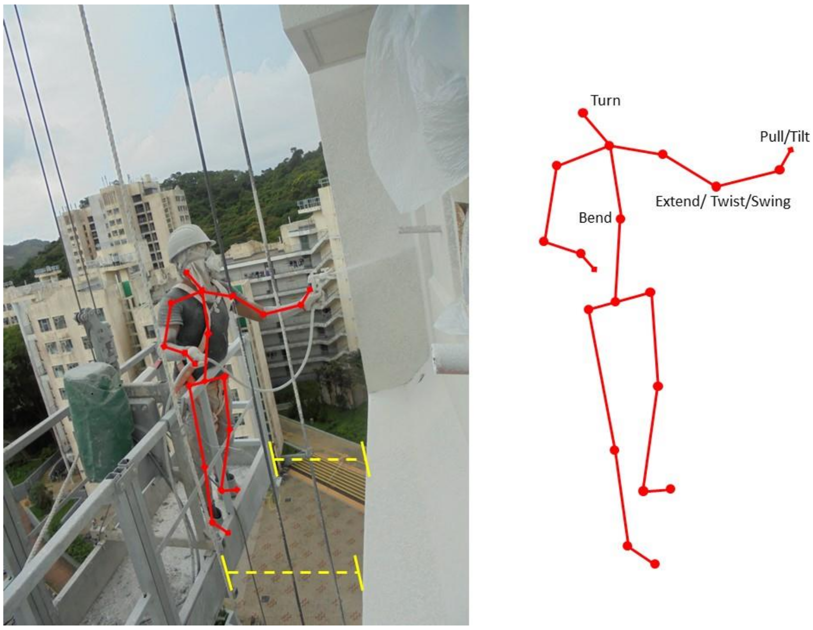


Figure 39: The dynamic analysis of the worker.

Information acquisition concerns sensory processing, for example, prior to the painting process, the labour to observe and touch the wall surface and to gather relevant data. The one who performs the task will memorize the data in this case, in other cases; the data will be kept in writing. In terms of the human operation, during the information analysis stage, the memorized information will be registered in the brain. The brain will provide temporary storage for the data, and the information is analysed and manipulated based on either the worker's previous experience, received training, and given instruction (Baddeley, 1992). Based on the data analysis and manipulation, the decision will be made in the decision selection stage. Finally, according to the decisions, implementation, as well as action plans, will be decided (Broadbent, 1958).

As can be seen from Table 43, the basic tasks are listed, and the four stages of information processing are described briefly. Evidently, the majority of the task is to inspect what human labour may rely on the expertise and previous experience to make judgments and decisions. Even though, from a technical point of view, the four stages of human information processing can be translated into an automated system function for OCR (Sheridan, 1998). Even if a realistic and feasible process is to be implemented, it is important to be aware of how automation performs the same function. Essentially, when applying automation, the four stages of human information processing can be translated into four automated functions. Namely, these functions are acquisition automation, analysis automation, decision automation, and action automation. After establishing an automated information processing strategy, the system designer needs to evaluate whether automation should be applied to a specific task or part of the information processing stage.

Table 43: Human information processing during the external façade painting process.

Human information processing				
Tasks	**Information acquisition**	**Information analysis, to judge and understand**	**Decision selection**	**Action implementation**
Equipment check	Information related to the spray gun, air compressor, fluid/ air hose, gondola	If the spray gun is fitted with the correct paint nozzle (tip) size	Through testing, and observing the spray patterns	If yes: carry on the task
				If no: change to the correct setting or exchange parts
		If the air compressor and sprayer is set with the correct air pressure	Through testing, and checking the compressor	If yes: carry on the task
				If no: reset the compressor
		If the length and diameter of the fluid/air hose is correct	Through visual observation	If yes: carry on the task
				If no: exchange the hose
		If the hand tools are prepared	Through visual observation	If yes: carry on the task
				If no: replenish the missing tools
		Gondola operation	Safety inspect and check through observation	Either carry on or stop the operation
Check the wall	Information related to the wall, and spray gun	The features of the wall	To be aware of the geometry, design configuration of the wall	Proceed to the next task
		If the wall is ready for painting	Through visual observation	If yes: prepare to paint
				If no: clean, brushing off the excessive dirt
		The position of the lead stroke and the lag stroke can be determined	Through visual observation	To start painting in the right position
Check the paint coverage	Information related to painting quality, wall coverage	If the paint surface is even	Through visual observation	If yes: proceed to the next section
				If no: paint over it again
		When/where to apply the overlapping technique	Through visual observation, define the surfaces	Use the technique for the appropriate wall surfaces
		If the thickness of the paint is correct	Through visual observation	Apply adequate technique
		If the distance between the wall and the spray gun is correct	Through visual observation and body coordination	Aiming the spray gun at the correct distance
Check the material usage	Information related to painting supply	If the paint is fully loaded	Visually or verbally check	If yes: Proceed to the next task
				If no: Refill the paint

Acquisition automation: Acquiring information automatically utilizes the sensing and storage of input data. The lowest automation level, the input data will be entered by a human operator. So the system only processes the input data and respond accordingly. For example, the human operator enters the robot coordination and dynamics of the manipulator manually either using on-line or off-line programming. This technique is often referred to as programming by demonstration (PbD). However, this technique requires the operator to possess extensive programming knowledge. Recently, many industries have adopted programming-less robot teaching techniques that allow a worker without expert programming knowledge to change robot performance parameters by using a portable handheld teaching pendant (Lee and Kim, 2013). In the next automation level, mechanical sensors will be used to carry out a sensing task. For instance, the limit switch will detect the object and transfer the data once the physical connection has been made, thereby the program will decide how to execute the data automatically. In higher automation level, proximity, optic, infrared, LIDAR, and laser sensors will be used to detect the object without any physical contact, thus to provide information related to the detected object to the control system. The highest automation level applies to scan the object, and then the system will be trained by using ML technology.

Analysis automation: Most data will be analysed automatically; the level of automation in regards to information analysis is determined by how the information is being managed. The lower automation consists of a direct translation of the input data without further processing (Lewis, 1998). For example, in case of emergency, when input data instructs the system to stop operating, then this command will bring the system to a sudden stop. A high level of automation requires system integration, which is able to process multiple layers of variables and to make decisions or perditions according to the program. For instance, when the program instructs the servo motor to move, and the proximity sensor detects the certain distance between the sensor and an object, consequently the program will analyse the data and determine if sending an instruction to stop the servo motor is necessary. The higher level of automation can use the input data to define if there are any anomalies that are different or similar to the previous input, and then the decision will be carried out based on the system memory.

Decision automation: Automated decision-making refers to the augmentation or replacement of a human's action in the decision-making process (Azadm, 1988). In lower automation level, the system will generate a guideline that acts as a reminder or instruction for the operator to make the final decision on how to react to the situation. For instance, the system asks the human operator to confirm if the surface is ready for the next coating, thus the operator will use observation and experience to decide whether to allow the system to proceed. In a higher level of automation, the system will decide and execute the task automatically, and only inform the operator if the system decides to.

Action automation: Automation in action implementation refers to the final execution of an action. A lower level of automation consists of the operator to press a bottom that confirms the operation go-ahead. Alternatively, in the higher automation mode, the system acts autonomously without any human interaction. However, when dealing with high-risk functions, if automation is mandatory, then it is vital that the system retains a certain level of human action and applies a moderate level of automation (Parasuraman, Sheridan and Wickens, 2000).

In Table 44, tasks associated with automated information processing are sequentially ordered. The four stages of information processing procedures are analysed in three aspects: first, identifying the main activity associated with the specific task; Second, estimating the level of human interaction required to carry out the identified activity; and third, evaluating the automation level that is associated with the corresponding human interaction level. In general, when there is lower human interaction related to the task, there is a higher level of automation. In contrast, a higher human interaction level means a lower automation level.

Table 44: Automated information processing during the external façade painting process.

Automated information processing				
Task	**Information acquisition**	**Information analysis**	**Decision selection**	**Action implementation**
Equipment check (spray gun & air compressor)	Activity: Self-diagnose	Activity: Determine system status pre-set information	Activity: Confirmation	Activity: Decide whether to process
	Human interaction level (HIL): low	HIL: low	HIL: high	HIL: medium
	Automation Level: High	Automation Level: High	Automation Level: low	Automation level: medium
localization	Activity: Detect position	Activity: Process data transferred by sensors and controllers	Activity: Whether the system is stable and level	Activity: Fully secure the position
	HIL: low	HIL: low	HIL: low	HIL: low
	Automation level: high	Automation level: high	Automation level: high	Automation level: high
Check the wall	Activity: Scanning in real-time or process input data	Activity: Process input data; Formulate the travel path for the spray gun	Activity: Confirmation	Activity: Start painting
	HIL: low - high	HIL: low - high	HIL: high	HIL: low
	Automation Level: Low - high	Automation level: high	Automation level: low	Automation level: high
Painting	Note: In this case, the painting speed, whereabouts to apply the overlapping technique, and the distance between the spray gun and the surface will be programmed and tested.			Automation level: high
Check the material usage	Activity: Check Paint level	Activity: Process data from the Liquid differential pressure sensor or similar	Activity: Whether to top up	Activity: To top-up
	HIL: Low	HIL: Low	HIL: Low	HIL: high
	Automation level: high	Automation level: high	Automation level: high	Automation level: low
	Activity: Project program; Schedule; Procurement data;	Activity: Process input data	Activity: Output confirmation	Activity: Communication

Process control	Labour availability			
	HIL: high	HIL: low	HIL: high	HIL: high
	Automation level: low	Automation level: high	Automation level: low	Automation level: low

From the analysis, it is clear various levels of automation can be considered for each identified automated task. Potentially, the highest level of automation is identified in localization, checking the wall, and checking the material usage process. An additional procedure is in place to determine which level is the most appropriate level of automation to evaluate the potential system function in conjunction with the hypothesized human performance consequences as if automation had been applied. Finally, there is a procedure to question the feasibility as well as reliability associated with automation. Hypothetically, automation imposes both a positive and negative impact on human performance (Parasuraman and Riley, 1997). Therefore, human performance consequences are to be regarded as the primary evaluative criteria and automation feasibility, whereas reliability is to be referred to as secondary evaluative criteria. In this case, four human performance categories will be discussed, including metal workload, situation awareness, complacency, and skill degradation.

1. Mental workload: an appropriate level of automation should keep human mental work at a reasonable level, and augment human efficiency. For instance, during the decision selection stage, a lower level of automation will allow the system to offer various operations highlighted in different colour tone to indicate different hierarchical order, which assists the operator in selecting the relevant decision. The graphical user interface (GUI) should be designed to be user-friendly, requiring minimal training. Sometimes automation can over-complicate human performance by adding additional task on top of the existing workload. For instance, when automation requires extensive time to set up the operational environment, then this type of automation will increase labour cost and increase the human workload both physically and mentally (Vicente and Rasmussen, 1992). However, the exception is that if the cost of the additional work resulted from adopting automation is low, yet the overall performance has been increased significantly, the additional work is justifiable.

2. Situation Awareness: system function automation can reduce human awareness of the operation and the working environment. Predominantly, the human will rely on automated feedback to make a decision, instead of making a personal judgment based on observation or experience. Faulty feedback generated by an automatic system could impose serious operational health and safety concern (Endsley and Kaber, 1999).

3. Complacency: similar to the situation mentioned previously that when the system is highly automated, yet not reliable. This will cause implications on each stage of the information processing activity. In particular, it is indispensable when the system provides unreliable data analytics and the operator uses the data as a reference to make the execution plan (Parasuraman, Molloy and Singh, 1993).

4. Skill degradation: if the majority of the tasks are performed autonomously, in the long run, the operator will lose the skills to carry out the task manually. This is critical when automation failure occurs and the operator needs to investigate the situation and take over the on-going task smoothly (Andrew M, 1989).

This method analyzes the human performance implications, which provides a guiding principle in the design of what should be automated, the level of automation and the pros and cons of automation and human-robot collaboration (Parasuraman, Sheridan and Wickens, 2000).

In addition, automation should not impose a threat to the operator or damage the system in the event of system failure. When considering all four human performance categories before the system design stage, a suitable level of automation and human-machine interaction can be determined. There are two secondary evaluative criteria besides the human performance consequences; one is technical feasibility and reliability, and the other is implementation feasibility. Technical feasibility refers to whether or not the proposed automated functions can be achieved by utilizing the existing technology at a reasonable cost. Automation reliability addresses the software and hardware integration is capable to carry out the specific function under the explicit operational environment by providing consistent reliable performance.

Many construction tasks can be automated, but when the costs of automating are greater than the potential cost-benefits, then adopting a higher level of automation will not be justifiable. While, in low-risk operation, if the system constantly requires human interaction and making every minor decision and is not able to perform the priority task, in this case, the automation level needs to be increased. It is often recommended to apply a lower level of automation for high-risk functions and to apply a higher level of automation for those tasks with lower risk functions. It does not mean high-risk function should not be automated. It is important when applying a higher level of automation to the higher-risk function that in the case of system failure the operator can take action on time to address the situation. Implementation feasibility refers to the feasibility to implement a particular level of automation, regardless of the infrastructure, policy, and regulation permit the deployment. Furthermore, there is a need to compare automation and human to determine if automation can match or exceed human performance. The tasks that human outperforms automation yet with less cost should not be automated. This method offers an indefinite approach to decide whether to apply automation or not, yet in practice, the factors such as what has been mentioned earlier need to be taken into consideration in every task and then determine the appropriate level of automation (Sheridan, 1998).

As mentioned earlier, to decide the level of automation can be guided by four stages of information processing activities, and with the recommended evaluative criteria, see Figure 40. The method can be used by the system designer in an early design stage to decide what task should be automated and with what level of automation. Therefore, it is important to understand the external wall painting sequence, as well as information processing strategy in both the conventional manner and the proposed automated process.

This exercise will help the system designer lay the foundation for developing the program architecture, control method, and system integration strategy for the proposed OCR, see Figure 41. The detailed system specifications and integration methods have not yet been decided. The system design decision will be influenced by the analysis conducted during this stage.

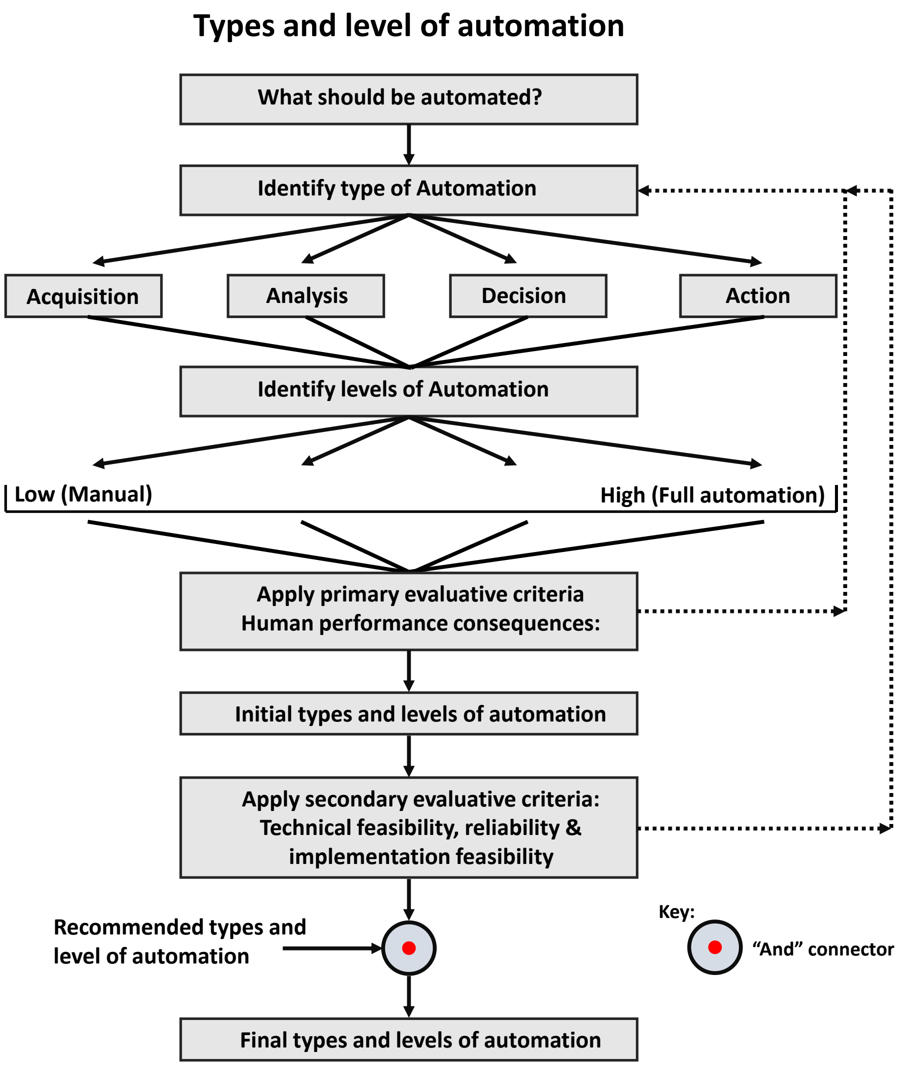


Figure 40: Flow chart showing the different types and the level of automation, based on (Sheridan, 2001).

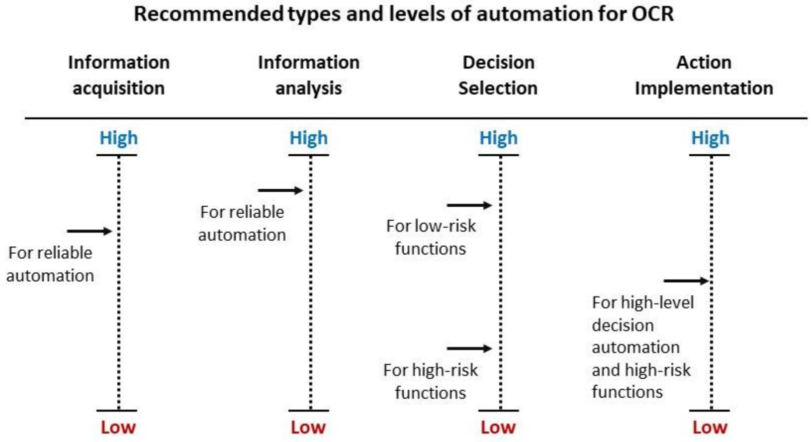


Figure 41: The recommended types and levels of automation for OCR, based on (Sheridan, 1998)

3.6.2 Primary design

In this section, the common external façade designs and construction method in Hong Kong PHC sector will be described. To investigate the surface areas that need to be painted, the methods are based on the geometry and designs of the façade to draft the initial kinematics design of the proposed OCR.

The prefabrication techniques have been wildly used in Hong Kong PHC sector. The specification of the design was approved by the BD, hence the design and configurations of the panels are very similar between various contractors. As shown in Figure 42 the external façades share a great similarity, even though they were constructed by three different contractors.

Figure 42: The typical types of public housing façade design in Hong Kong, source: (Wen Pan).

The most common types of precast concrete façade (PCF) can be seen in Figure 43. The case study building is a typical Harmony block construction style, which adopted the post-installation method. The post-installation process consists of hoisting the PCF into place and the connection between the panel and the floor is usually bounded with grout, and the joints are to be made watertight with silica infill or silica strips (Jaillon and Poon, 2009).

The author has asked the project manager why the PCF is not painted off-site in the prefabrication factory. The project manager said the PCF will be inspected on-site for cracks after the curing process, therefore; if the PCF is painted in the factory, then the cracks will not be visible. On top of that, damages might occur during transportation and hoisting, so even if the PCF is painted off-site, the worker still needs to double-check once the installation task is completed. The dimensions of the PCF are non-standard, usually, the length is between 2300 mm and 4700 mm, and height is between 2700 mm and 3000 mm. The UPVC window frame is cast with the panel off-site; it is covered with a layer of plastic wrap to protect it from scratch. The PCF surface consists of flat surfaces and protruding features, which offers the distinctive appearance of the Hong Kong public housing style. The large protruding section is to be used as an air conditioner support platform, which is an integral part of the PCF. The air conditioner is a necessity for the local resident. To ease installation procedure, all PCF used in PHC is designed to bear this feature. At the bottom and the side of the PCF, there is an overhang feature. The bottom overhang edge normally contains an overlap of approximately 370 mm. These overhanging sections provide shading during specific hours of the day, see Figure 44.

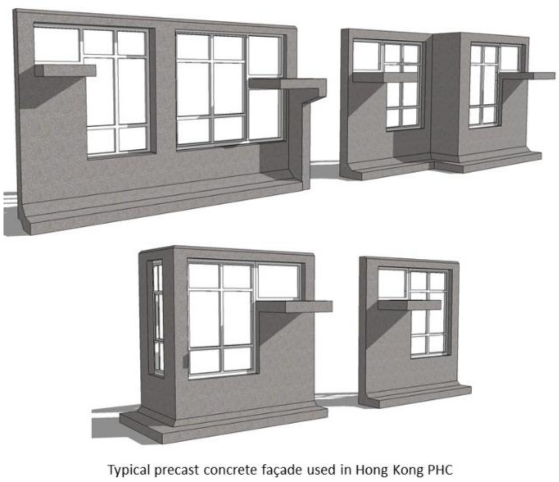


Figure 43: Common types of precast concrete façade panels.

As demonstrated in Figure 44, during the hottest hour of the day in Hong Kong, for example, between 12:00 pm and 13:30 pm, the overshadowing effect provided by the overhanging feature is evident. In addition, another function of the bottom overhang is to divert rainfall during the subtropical monsoon seasons in Hong Kong. The sloping edge prevents the rain from the façade and the offset will direct the rain away from dropping on the panel below, so that both the moisture and the exterior paint finish are kept apart, see the image on the right, see Figure 45.

Figure 44: The overshadowing design feature of the precast concrete façade panel.

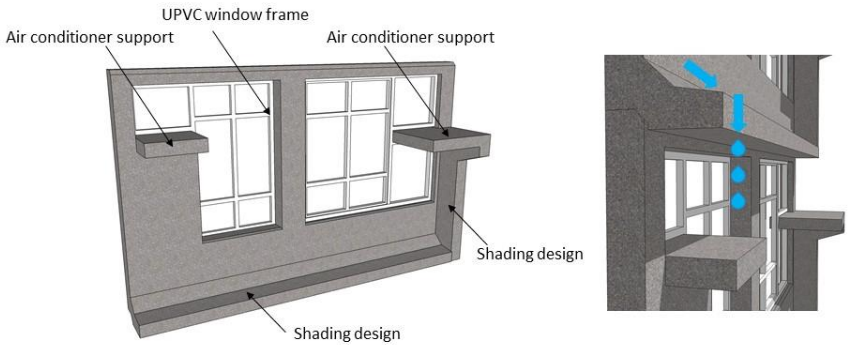


Figure 45: The design features of the precast concrete façade panel.

Given that the irregular geometry, the uneven surface will possibly impose more difficulties during the painting process, especially when considering adopting OCR in this case. The method used to analyse the surface attributes of the case study PCF is to use different colour tones to indicate various features and based on the analysis the designer can propose an initial kinematic design for the painting function, see Figure 46. The flat surface is marked in green that requires motion along the X, Z-plane. The protruding section that is in the same vertical plane as the flat surface is marked with red, which requires movement along the Y-axis. The upper section of the protruding part is marked in blue, which requires movement along the Y-axis and pitch around the rotational joint. The opposite section of the protruding part is marked in yellow that demands movement along the Y-axis with pitch around the rotational joint. Either side of the protruding part is marked in brown, which demand movement along the Y-axis and yaw around the rotational joint. Finally, the slopping section is marked in orange, which demands movement along the X-axis and pitch around the rotational joint. One of the immediate challenge faced by the designer is to seek an economic approach that enables the system to be able to reach and cover all planes of the PCF. Thus implementing a typical industrial robotic arm with six-DOF appears to be infeasible, firstly because of the high costs, and secondly because of the limited travel path, for example, although the robotic arm could provide yaw and pitch motions, it cannot cover the entire geometry length, height and width. Nevertheless, it will require additional movements that cover the distance along the X, Y, and Z-axis.

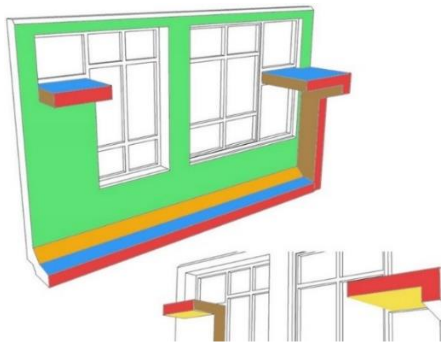


Figure 46: Façade feature analysis by using different colours.

In regards to the kinematic design, the robot processes five DOF that consists of three translational joints, which offer movement along the X, Y, and Z-axis, and two rotational joints that offer yaw along the X-axis, and pitch along the Z-axis.

The kinematic model of the localization system is shown in Figure 47.

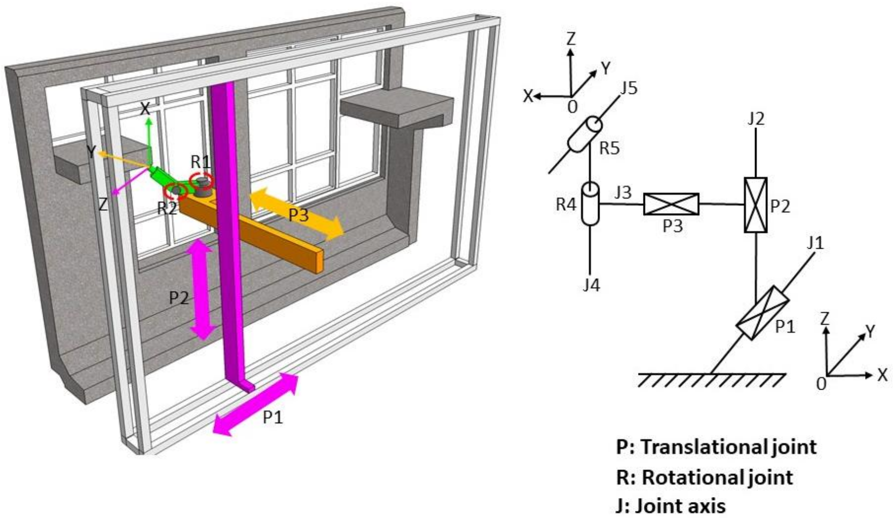


Figure 47: Kinematic structure of the proposed OCR.

Based on the Denavit-Hartenberg (D-H) convention, the coordinate transformation between two consecutive link frames {i-1} to {i} can be defined as:

$$^{n-1}T_n = \mathrm{Rot}_{x_{n-1}}(\alpha_{n-1}) \cdot \mathrm{Trans}_{x_{n-1}}(a_{n-1}) \cdot \mathrm{Rot}_{z_n}(\theta_n) \cdot \mathrm{Trans}_{z_n}(d_n), \quad (1)$$

where $\mathrm{Rot}_{x_{n-1}}(\alpha_{n-1})$ defines a rotation of angle α_{n-1} around the x_{n-1} axis, and $\mathrm{Trans}_{x_{n-1}}(a_{n-1})$ defines a translation of a_{n-1} along the x_{n-1} axis. The transformation matrix $^{n-1}T_n$ is a composition of rotations and translations to move from a frame $\{i-1\}$ until it coincides with the frame $\{i\}$.

Table 45: The D-H parameters of the localization system model.

α_{n-1}	a_{n-1}	θ_n	d_n
$-pi/2$	0	0	d_1
$pi/2$	0	$-pi/2$	d_2
$-pi/2$	0	0	d_3
$pi/2$	0	$\theta_4 + pi/2$	0
$pi/2$	0	θ_5	0

Accordingly, the D-H parameters for this model are shown in Table 45, where d is the offset along the previous z to the common normal, θ is the angle about the previous z, from old x to new x, a is the length of the common normal (assuming a revolute joint, this is the radius about the previous z), and α is the angle about common normal, from old z-axis to the new z-axis.

With the D-H parameters, the transformation matrix from the robot base frame to the end effector can be calculated using joint variables. The end effector orientation can be obtained by multiplying the transformation matrix as follows:

$$^{0}T_e = {}^{0}T_1 {}^{1}T_2 {}^{2}T_3 {}^{3}T_4 {}^{4}T_5 {}^{5}T_e, \quad (2)$$

Where $^{n-1}T_n$ is the transformation matrix as shown in (1)

The case study building has three main surface types, include the area features with narrow flat surfaces with windows, the aforementioned PCF, and the façade area with large flat surfaces but without windows, see Figure 48. Thus, the proposed OCR will cover those types of surfaces when it is equipped with five DOF and the combination of translational and rotational movements.

Figure 48: Three types of façade designs of the case study building.

At this stage, a comprehensible development strategy of the proposed multifunctional façade finishing robot has emerged. In particular, More explicit functional and non-functional requirements are identified as a result of the previous studies. The allocation of function, level of automation and the initial kinematic design of the proposed OCR are to be confirmed and will be detailed in the next stage.

Functional requirements for the proposed OCR collected from the initial design stage:

- Compatibility: The proposed OCR need to be compatible with Hong Kong PHC sector, which is compatible with the most common types of façade designs. The robots do not perform the alteration of any other structural element or additional fixtures to the existing building.
- Functionality: The proposed OCR should perform painting and localization task autonomously. In addition, visual recognition and material usage checking should achieve a relatively high degree of automation.

Non-functional requirements for the proposed OCR collected from the initial design stage:

- Usability: The proposed OCR will not add additional tasks on top of the existing workload. The GUI and operation method is user-friendly, and the system does not take a long time to set up. Moreover, the OCR can be used in the weather conditions that match human tolerances or guided by regulations.
- Technical feasibility: The proposed OCR should utilise as many off-the-shelf components as possible. If there is something that needs to be developed from scratch, then the development should not exceed the planned schedule or costs.
- Reliability: Under a standard operational environment, system software and hardware

can offer continuously reliable services. The system is easy to maintain and malfunctioning parts can be easily replaced.

3.6.3 System configuration

As stated in the research scope, the development work in regards to programming, detailed hardware and software integration is beyond the scope of the project. This chapter describes how the system being developed is influenced from the outcomes from the previous studies, namely survey, on-site visit, co-creation workshop, allocation of function, and the analysis on the type and level of automation.

In Hong Kong, PHC painting task is carried out by using the suspended working platform or gondola; this method has been approved by the BD and overseen by the code of practice for safe use and operation of suspended working platform issued by occupational safety and health branch of the Labour Department (LD). During the co-creation workshop, the industry practitioners and the representatives from the BD recommend that the proposed OCR should preserve the working principle in terms of hardware use and operational method.

The proposed OCR is therefore built on the basis of the traditional suspended platform model to incorporate the robotic functionality as an extension to the existing equipment. Another design challenge is how to adapt to the typical PHC design while exploring the potential for system upscaling. As mentioned previously, the existing PCF composes rather complicated geometric shapes; five DOF is required to ensure the majority of the surfaces are covered. Furthermore, there needs to be a developed a proof of concept (PoC) method for building façade detection and recognition without using costly and high sensitive sensors.

The multifunctional façade finishing robot adopted a platform-based versatile product design principle, which enables the product to share a set of parts, components, frame structure, hardware, software interfaces, and production methods amongst the various market demands and product upscaling (Meyer and Lehnerd, 1997). The proposed OCR consists of ten key components, including the suspended working platform (gondola), supporting frame, end-effector, actuators, stabilization system, retractable vacuum cups, control system, power supply, detection system, airless spray compressor, and the main and reserve paint tanks, see Figure 49.

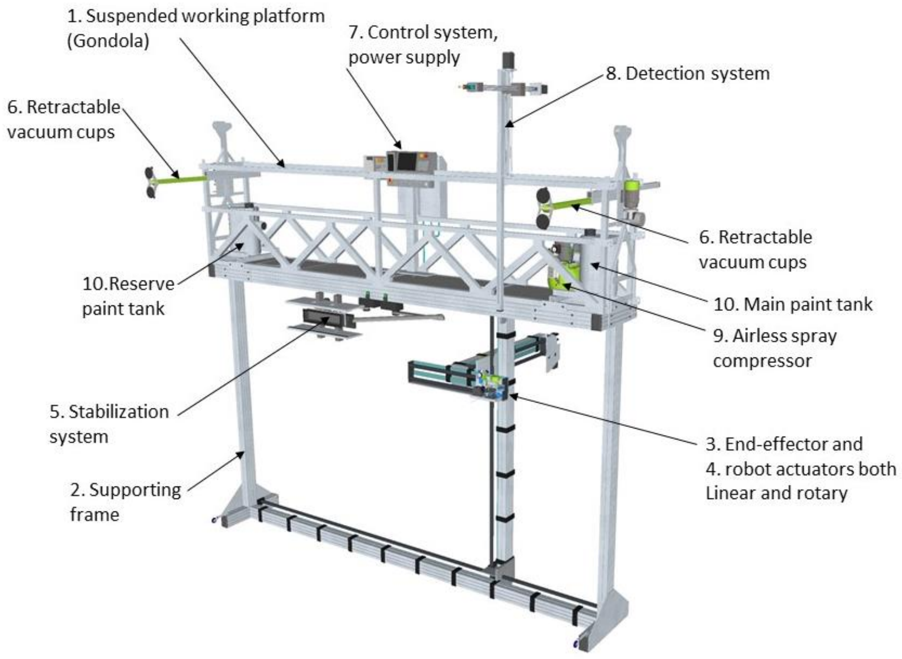


Figure 49: The key components of the proposed OCR.

The main components and the brief descriptions of their function are illustrated in Table 46:

Table 46: The functions of the key components.

Component		Function description
1	Gondola	To provide a working platform for the operator when necessary. To accommodate the subsystems such as, the retractable vacuum cups, paint tanks, airless compressor, control system, power supply, and upholding the supporting frame.
2	Supporting frame	To accommodate the linear actuator tracks, the stabilization system, and the end-effectors.
3	End-effectors	Interchangeable end-effector fixture that allows the system functions to be changed according to the demand.
4	Actuators	Include linear and rotary actuators, which offers vertical, horizontal, rotational movements of the robotic system.
5	Stabilization system	To clamp, and to position the system on to the building façade.
6	Retractable vacuum cups	To offer a final stabilization solution of the system.
7	Control system and power supply	To accommodate control panels, inverter, and power supply devices.
8	The detection system, power supply	To detect the specific feature of the building and in response to the stabilization system.
9	Airless spray compressor	It is the key part of the spray system, which does not use compressed air to break down paint fluid into atomizing particle. It is compatible with the HPC specified paint coating specifications.
10	Main and reserve paint tanks	To supply paint materials to the spray system.

The dimensions of the system are slightly larger than the size of the PCF that is commonly used in Hong Kong to provide a comprehensive working range. For instance, the width of the PCFs used in the case study building is between 2090 mm and 4665 mm, and the height is 2825 mm.

Therefore, the robot is to be designed to provide a maximum working range of 3470mm in height and 5050 mm in width, see Figure 50. Essentially, the gondola is above the working area, which means the operator can easily inspect the work quality of the robot once the system descends from one floor to another. The components below the gondola will be referred to as the main operational section.

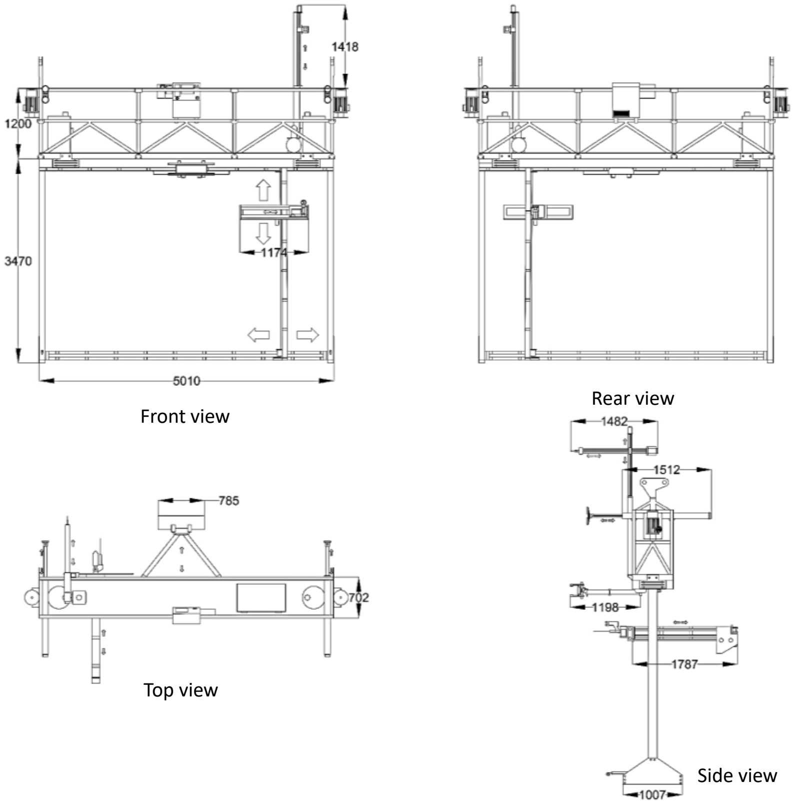


Figure 50: The dimensions of the proposed OCR.

The composition of the robot can be seen in Figure 51. The gondola is situated on the upper section, and the robotic actuators and end-effectors are located at the bottom. The advantages of this configuration are: the gondola provides a platform where the operator can control the robot, inspect the paint finishing, and rectify the areas where require human interaction.

To enable the maximum flexibility and to ease system upgrading, installation, maintenance, and transportation, the system bears a modular feature. Most of the components located on the gondola are demountable. The retractable vacuum cups are installed on the gondola balustrade that can be adjusted to suit the shape of the PCF. The detection system is also mounted to an adjustable frame, and the location can be changed depending on the construction façade layout. In the case of maintenance or system upgrading, those components are easily accessible and can be interchanged quickly. Figure 52 shows the exploded view of the robot.

The main operational section is detached from the gondola; in fact, the two sections are connected with six steel fastening plates. Due to the overall dimension of the robot, potential issues could occur in terms of transportation if the system cannot be dismantled. The system can be disassembled into manageable sizes, which is fastened by simple slots with bolted connections. The electrical wiring and cables are protected by enclosed cable towing drag chains to ensure the cables are kept untangled, especially during operation. The connection of the cables is designed to follow the principle of the plug-and-play method, which allows rapid and accurate installation.

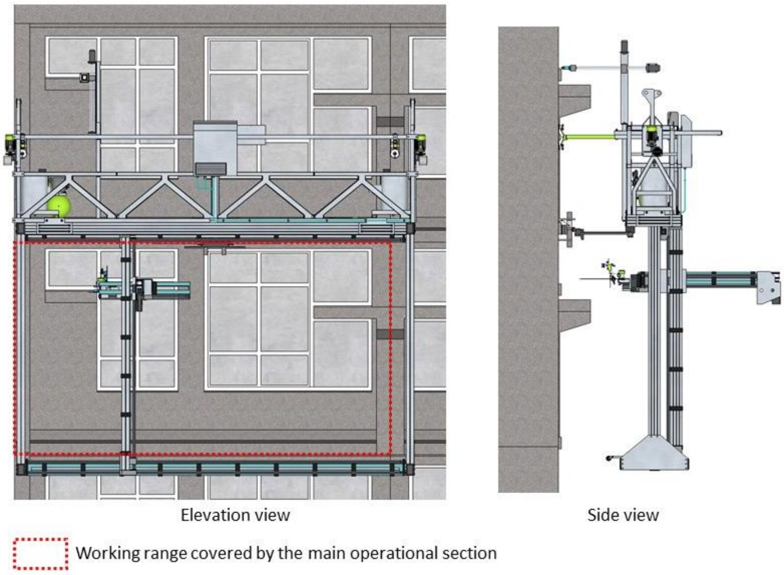


Figure 51: The composition and working range of the proposed OCR.

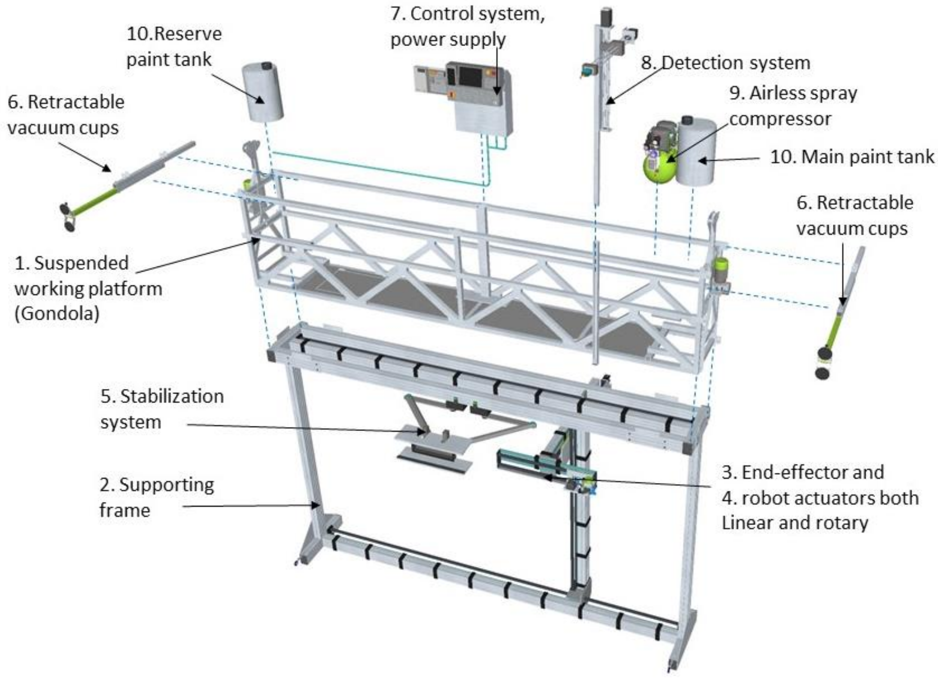


Figure 52: The exploded view of the proposed OCR.

The components and parts of the robot, excluding the gondola, can be loaded and packed into a standard 20 ft intermodal container. This offers great mobility and usability because most of the container lorries or 10-12 tonne trucks are able to transport the robot without any further vehicle modifications. The left side of Figure 53 shows the components from the main operational section, and the picture to the right shows the internal configuration of the shipping container, which illustrates how parts and components are packed. In addition, the gondola will be transported with its own package, which is a standard accessory.

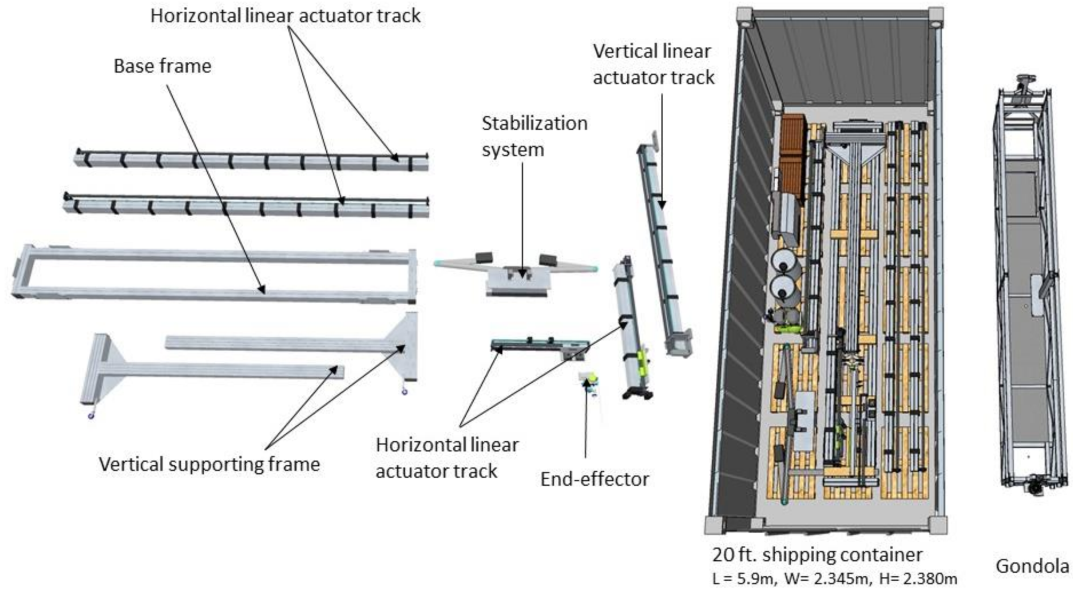


Figure 53: Transportation and logistics strategy of the proposed OCR.

The robot can be supported by the conventional gondola roof support system. The roof support system consists of two key components: steel outrigger beams and parapet clamps. The main functions of the outrigger beams are to allow sufficient cantilever, as well as to support the hoisting cables. The parapet clamps are securely fastened on to the reinforced concrete parapet wall that supports the entire weight of the robot, the gondola, and the operator. The steel outrigger beams will be able to rotate at a certain angel that facilities the installation of the proposed OCR, see Figure 54.

The end-effector of the proposed OCR is not the same as the traditional sense of the gripper robotic end-effector. In this case, the end-effector consists of a linear actuator, two rotary actuators, and an automatic airless spray gun with interchangeable nozzle sizes. Take the GRACO AL Automatic airless spray gun for instance. The end-effector poses an elongated design as demonstrated in Figure 55. The spray gun can travel along the linear actuator track that enables the system to reach the target painting area located on the side of the building façade. The design enables the spray gun to bypasses the supporting frame, which otherwise would pose as an obstacle. In addition, in order to broaden the capability of the robot, an interchangeable end-effector system is proposed. Therefore, the robot not only can perform the façade painting task but also has the capability to perform other façade and exterior tasks without the purchase of a new robot. The iteration strategy and function up scaling potentials will be described in detail in the later section.

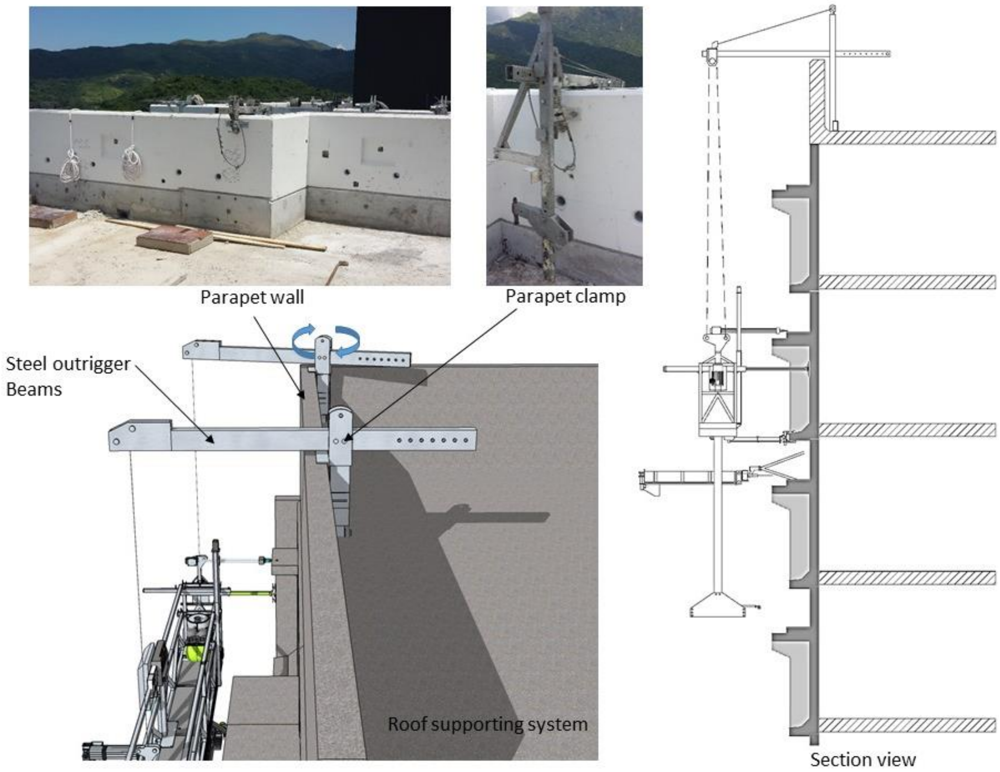


Figure 54: The design of the roof support system.

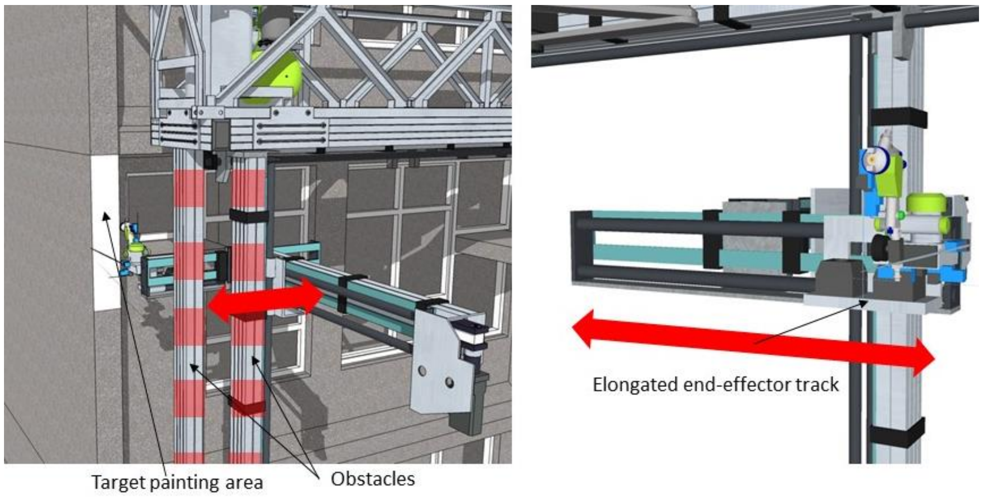


Figure 55: The motion of the end-effector.

The material supply system includes four components: a motor or drive system to power the pump, a pump to drive high-pressurized fluid to the spray gun, a pressure control system to monitor the paint pressure, and a refillable paint tank. Alternatively, if the material supply system will add additional weight to the system, in that case, the material supply system will be located in the building to reduce the weight of the robot.

The proposed OCR will be able to generate Direct Current (DC) voltage in conjunction with the required power inverter which converts DC to Alternating Current (AC) through standard compact power supply modules. The gondola can use a separate power source from the robot to power its standard stepper motors.

The principle control of the robot is facilitated by a feedforward control method that is combined with proportional–integral–derivative controller (PID) controller and implemented with the microcontroller or programmable logic controller (PLC). The advantages of the PID controller are model-free, the technology is mature, vastly applied in varies of industries, and it is highly suited for application that requires a high level of precision in control (Nelson and Stephen J, 1991). The communication protocols of the robot are divided into two separate modes, one is the manual mode, and the other one is the autonomous mode. The operator can switch between these two modes when desired. This is an extremely facilitative feature, especially in case of emergency and the human decision is required. The other two key systems, stabilization system, and the object detection and recognition system, will be described as a PoC in the later section.

3.6.4 Operational sequence

The painting operation includes many subtasks, which include system setup, system calibration, and painting. First, the author would like to propose the robot's operational sequence and explain the expected workflow, but not only the on-site function but also the overall workflow of the painting process when the proposed OCR is implemented. In practice, this exercise will assist the designer in anticipating the installation tasks, involved steps, and therefore, in planning and making sure the correct measure is taken into consideration before the work commences on-site.

The system setup will be carried out once the robot has been delivered on-site, which consists of the following steps Figure 56. The preliminary step is to install steel outrigger beams and parapet clamps on the roof level. As shown in Figure 56 and Figure 57, a sufficient loading area is needed to position the system components. The first step is to install the components that will be fitted on the gondola and to install the base frame while the gondola is slightly elevated over the ground level. The second step is to elevate the system up to an appropriate height that allows installation work to be carried out below the gondola. The third step is to install the vertical supporting frames on either side of the base frame. The fourth step is to install the horizontal and linear actuator tracks. The fifth step is to install the vertical linear actuator track and to connect the end-effector as well as the stabilization system. The sixth step is to carry out system calibration, which confirms the perimeter of the working range, the distance between the spray nozzles and the façade. The final step is to adjust the stabilization system and to set up the paint pump to the correct working pressure.

Setting the perimeter is one of the most important tasks while conducting system calibration. Similar to the industrial robot, the proposed OCR can be programed by a handheld robot teach pendant as an interface to teach the robot. The main task performed with the teach pendant is to teach location variables.

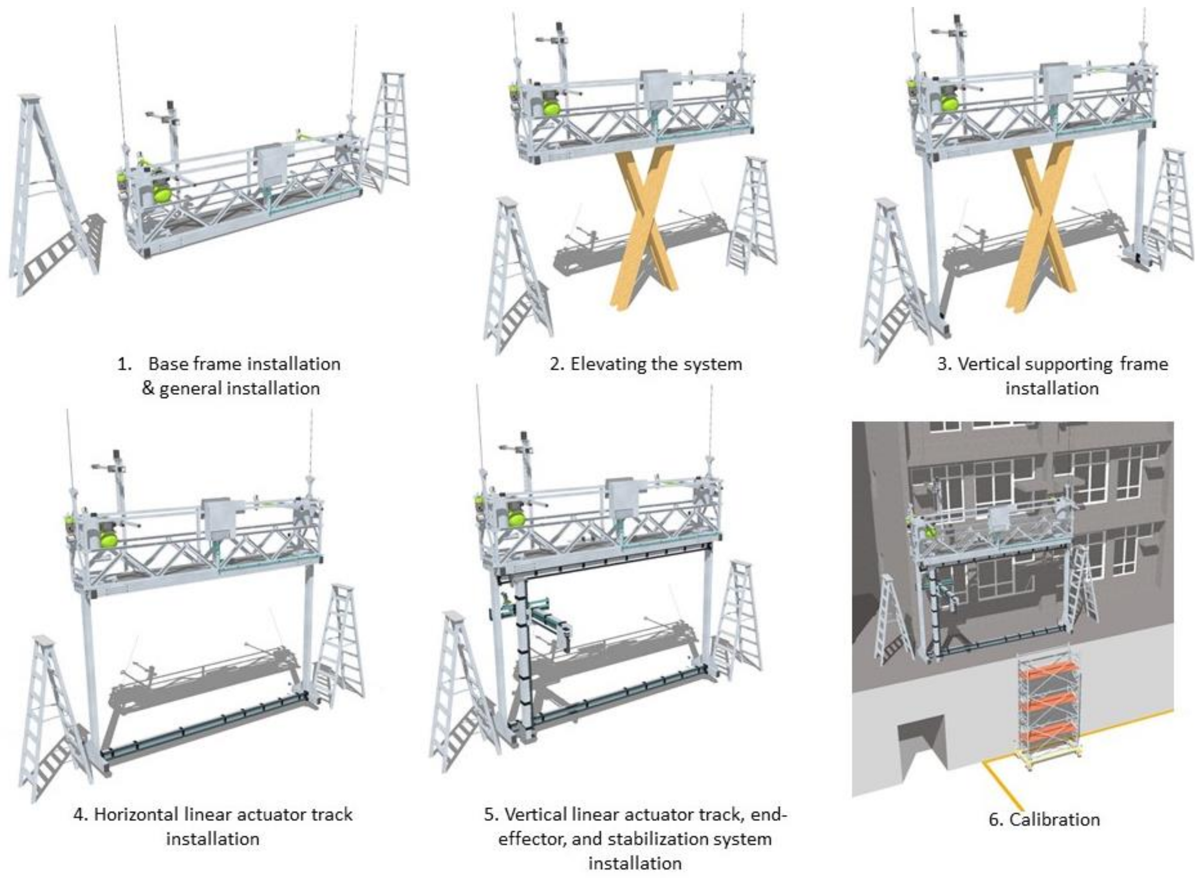


Figure 56: Detailed illustration of the system setup procedures.

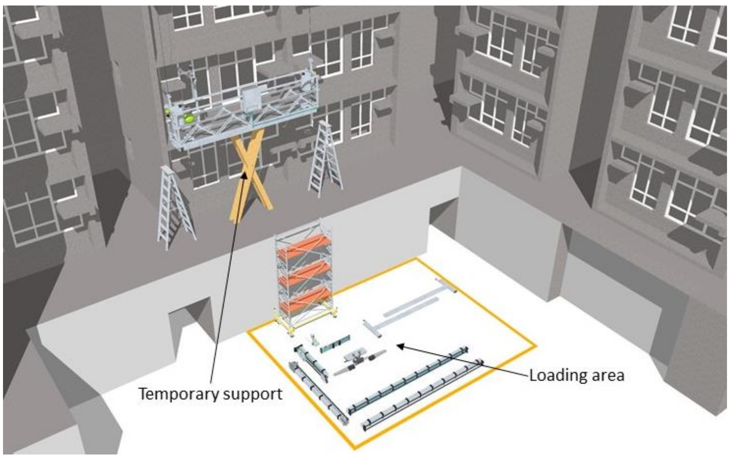


Figure 57: The designated loading area for on-site system installation.

In this case, location teaching involves positioning the end-effector and following a specific travel path along the façade. In brief, when a new location has been registered into the teaching command, the program overwrites the previous input and replaces it with the current location variable. The advantage of this method is the technology is mature, economic, and reliable, which is vastly applied in the other industries. However, the drawback is the system has to be reprogramed when dealing with different wall configuration. Even though the programming method consists of mainly data input and redirecting the robot end-effector, yet it is additional time that can be potentially saved. After system calibration, the robot will be hoisted up to the top floor and start descending while painting. When one section of the façade is completed, the robot will be decommissioned, and the system setup sequence will be repeated as shown in Figure 58.

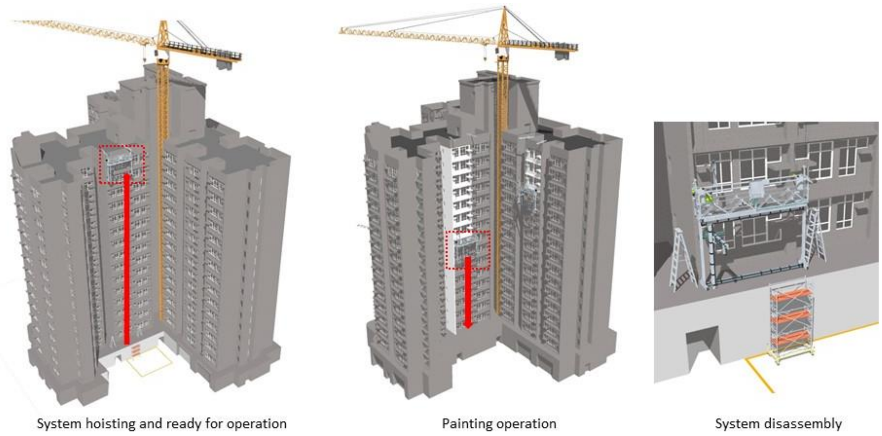


Figure 58: The overall system setup sequence.

Figure 59, Figure 60, and Figure 61 demonstrate how the spray nozzle navigates across three different types of PCF. The Type one is the PCF with protruding features; Type two refers to the wall with a flat surface, but with no window opening, and Type three refers to the PCF with windows. The red arrows indicate the direction of the paint stroke, the dotted blue line represents the travel path of the spray nozzle, the green arrows refer to the paint stroke on the upper part of the protruding section, and the purple arrows indicate the paint stroke beneath the protruding section.

To ensure even coverage of coating has been sprayed on the façade, a method called overlapping will be adopted. As indicated in Figure 62, the spray gun will overlap each stroke by 50%. When spraying a corner, the spray gun should be pointed directly into the corner and only applying paint vertically Figure 63. The nozzle sizes will be determined based on the material properties of the coating that will be applied. In practice, the distance between the spray nozzle and the façade should be kept at approximately 30.5 cm, and a brand new paint tip will cover a vertical strip with 30 cm width. In addition, based on the conventional manual technique, the spray gun should be aimed straight at the façade even when the spray gun is moving across the surface. The method called “Fanning”, which is when swinging the spray gun at the surface, is insufficient yet a common practice made by a painter and can cause an uneven finish. The motion control of the end-effector will take this into consideration, and will keep the spray gun aimed directly at the façade.

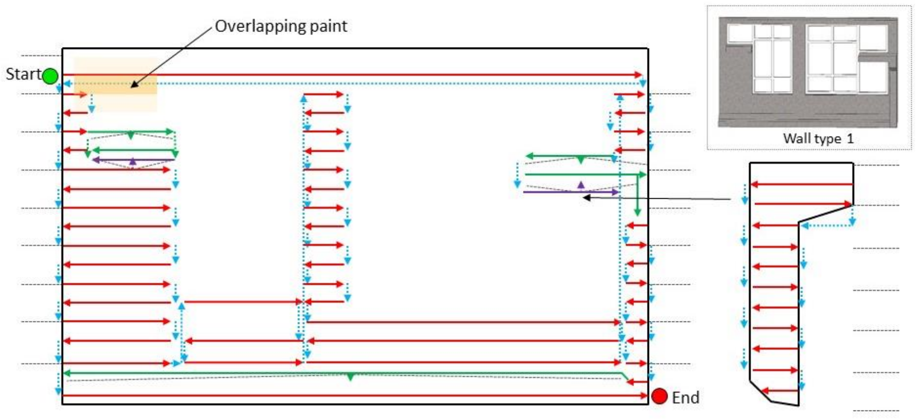


Figure 59: The nozzle travel path for the Type one PCF wall.

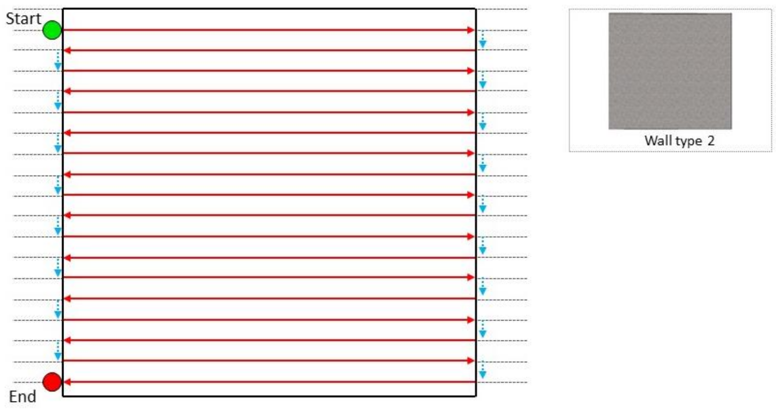


Figure 60: The nozzle travel path for the Type two PCF wall.

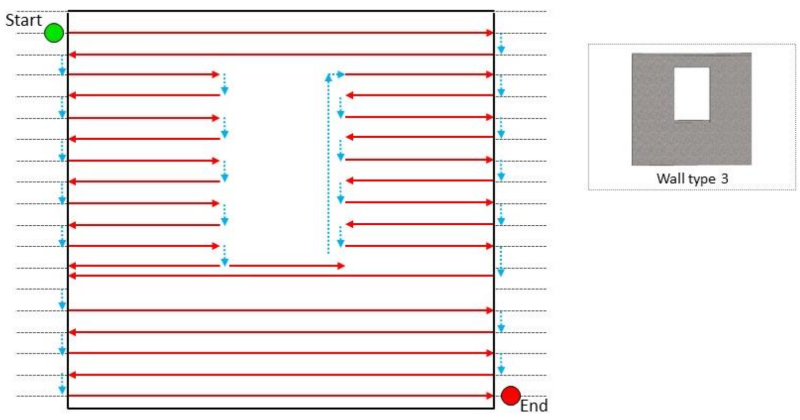


Figure 61: The nozzle travel path for the Type three PCF wall.

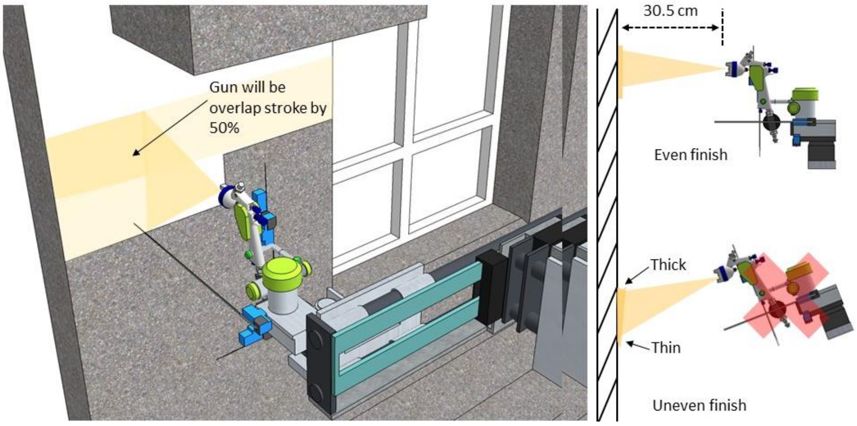


Figure 62: The overlapping painting method and the correct spray gun position.

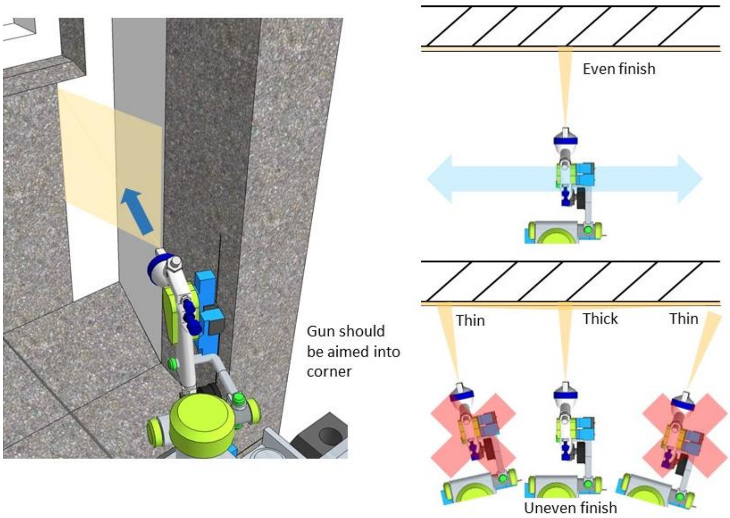


Figure 63: The correct position between the spray gun and the nozzle and the wall.

The design of the robot imposes certain limitations, which suggests the robot cannot cover the entire building surfaces. So, some areas still need to be painted manually. Because the gondola is situated at the top of the robot's main operating area, it will be placed right in front of the parapet wall when the robot is hoisted to the top of the roof. Therefore, the robot cannot paint the parapet wall. However, the design of the robot can still compensate such issue because the parapet wall can be manually painted by using the conventional gondola afterwards Figure 64. In addition, the dimensions of the robot determine that some of the narrow spaces across the building façade are restricted.

Alternatively, thanks to the flexible design, the robot can be reconfigured into a narrow dimension. Therefore, it can cover the maximum façade area. The overall floor plan of the case building is depicted in Figure 65. The areas marked in green represent the position that can be reached by the robot. In contrast, the areas marked in red represent the restricted positions to be painted either manually or by the narrow-sized robot.

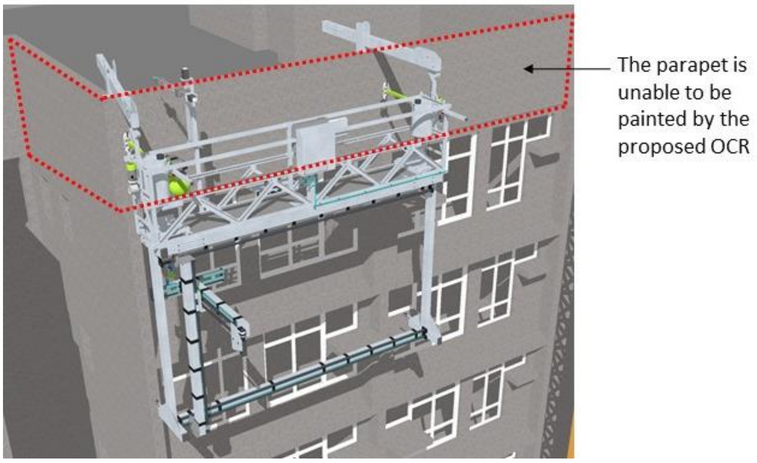


Figure 64: The area needs to be painted manually.

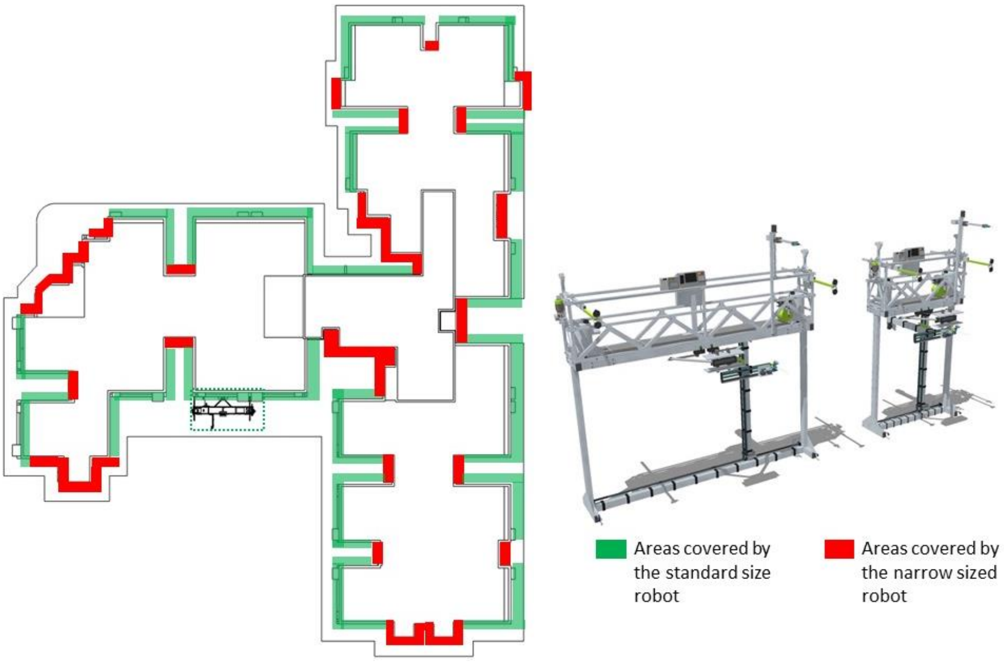


Figure 65: The indication of the areas that can be painted by various sizes of the proposed OCR or by a worker.

Let's assume a company that provides automated façade painting services, and supply the robot, then the expected overall workflow can be divided into ten steps Figure 66. Of course, this is an anticipated gesture; in practice, the business model adopted by the robot proprietor will influence the workflow.

Step one: Project pre-consultation focuses on discussing the project requirements, objectives, generally to provide an overall insight of the project to the project team and the client. Many issues can be discussed during the pre-consultation; the subjects may include building survey, operation strategy, project schedule, legal requirement, and payment plan.

Step two: Project planning will be carried out shortly after the project pre-consultation, which will map out the detailed project scope, to draw up the roles and responsibilities of each involved party.

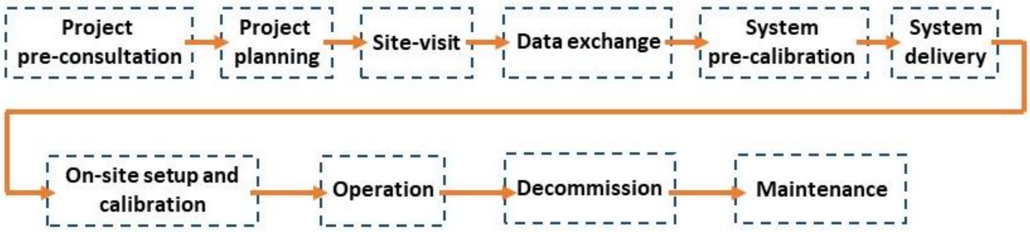


Figure 66: The expected workflow of the proposed OCR.

Step three: Site-visit provides first-hand information on the job site. The project team will use this opportunity to gather information with regards to site condition, building specifications, and the existing infrastructure, and to provide advice relates to on-site preparation prior to system delivery.

Step four: Data exchange consists of the transformation of information both in hard copies and in digital formats. Potentially, this process will be made more efficient if the client body is aided by BIM applications. However, when dealing with building measurement, before inputting any data, it should be double-checked against the data collected on-site. This is because digital data may not be accurate and reflects the actual condition of the building.

Step five: System pre-calibration measures the system performance under lab condition. The system will be calibrated based on the data collected from pre-consultation, site-visit, and data exchange activities. The system will be tested under the estimated on-site conditions to identify operational limitations, failures, and to propose feasible resolutions.

Step six: System delivery will focus on the identification of the most appropriate transportation means, routes, and cost. In addition, on-site logistics strategies will be planned prior to system delivery.

Step seven: On-site setup and calibration consist of installing steel outrigger beams and parapet clamps, setting up the robot as what has been described in the system setup descriptions.

Step eight: The objective of the operation step is to ensure an even layer of paint is applied to the designated location. During this step, a detailed working logbook will be documented. The information collected will provide valuable insight on system improvement. The detailed working algorithm flowchart is demonstrated in Figure 67.

Step nine: From a day-to-day operation point of view, decommission is dealing with system disassembly and removal. In terms of system life-cycle management, decommission will focus on system reconditioning and recycling.

Step ten: Routine maintenance will take place after the system is decommissioned. While the robot is working on-site, some consumables such as painting and nozzle tips will be exchanged or replenished.

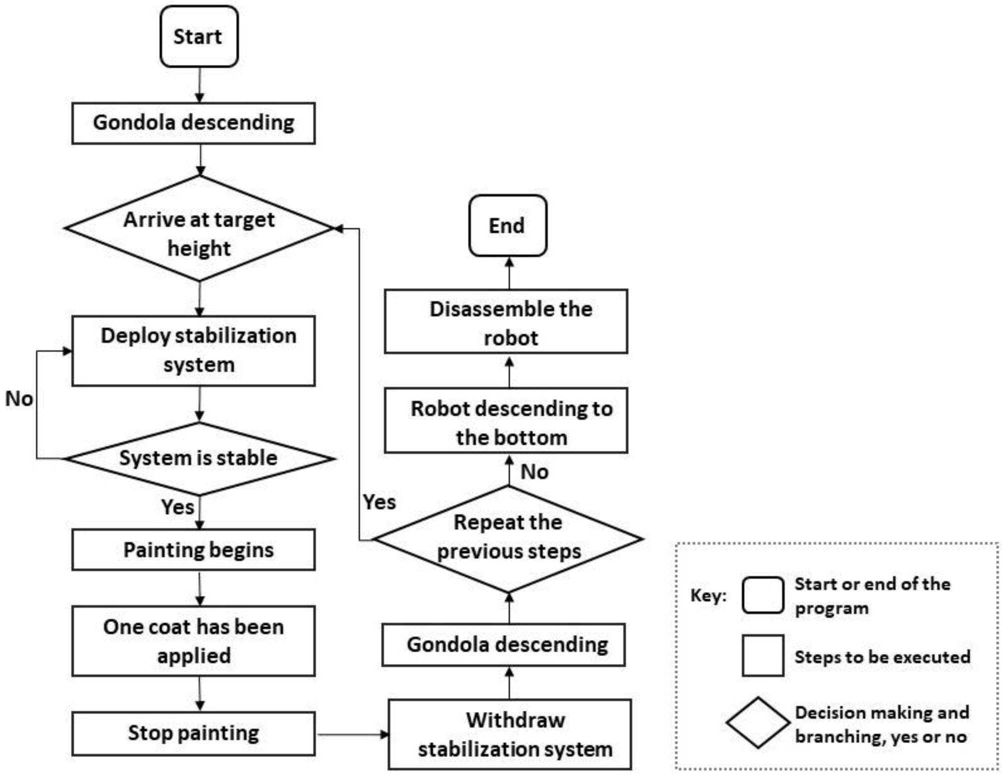


Figure 67: The proposed operational flowchart.

3.7 Supporting developments

Due to the nature of the external painting task, on-site condition, and the building design, completing the system requires extensive hardware and software integration. This section will introduce three key systems including the stabilization system, the object detection, and recognition system, and an information modelling system. The author worked closely with fellow researchers throughout the project phase. At the time of this writing, these systems are only developed as a proof of concept, yet they provide valuable insights for the detail design and development phase of the project.

3.7.1 Stabilization system

During the development stage, the project team has identified a number of issues, of which within the system positioning and stabilization imposes serious implication on the overall performance of the proposed OCR. First, the author has conducted research on the localization methods that have been used in the existing façade application robots. In general, the most common façade application robots include external rendering, cleaning, and inspection. Some of the examples are demonstrated in Table 47. They share a similar degree of freedom, to be operated under a comparable condition, and therefore, the localization method that is utilized by those robots may be influential to the proposed system.

Table 47: List of façade robots and their localization strategies.

Manufacturer	Robot	Country	Application	localization method	Façade type
Taisel	Exterior wall painting	Japan	Rendering	Guide rail	Vertical, flat
Kajima	Façade inspection robot	Japan	Tile façade inspection	Parapet, wall clamps and cables	Vertical, flat
Fraunhofer, SIRIUS	Glazing curtain wall cleaning robot	Germany	Façade cleaning	Wheels and cables	Protruding
Louvre, Robosoft	Glazing curtain wall cleaning robot	France	Façade cleaning	Vacuum cups	Vertical, flat

Through system analysis, combined with revising what has been discussed during the on-site study, and co-creation workshops, the proposed stabilization method was inspired by the aforementioned systems. However, each system was tailor-made based on a specific type of façade. Some systems require additional temporary fixtures or permanent guide rails. Both operations were strongly opposed by the stakeholders. Installing temporary or permanent fixtures to the PCF may increase the risks of damage, and this can create a liability dispute between the PCF manufacture, robot provider and the property developer. The systems mentioned earlier are designed to deal with flat surfaces, yet the complex geometry of the PCF used in the case study building imposes challenges in terms of maintaining good paint coverage and quality. To do so, the robot must remain stable during operation.

The biggest challenge facing the proposed stabilization system is developing a system capable of self-diagnosing the situation while adjusting the gondola and the main operation section to remain stable. The system is expected to stop at a target position. After stopping, the system should able to detect the current location in reference to the façade, and if the system is not level or movements can be detected due to external force or the momentum caused by inertia, the system then needs to be capable of correcting the position automatically. The design objectives of the stabilization system are that the system should not require any temporary and permanent fixtures. With minimum alteration, the system can be adapted to most common types of building designs. The stability of the main operation section will be improved, which will accommodate a diverse range of functions. In addition, the stability of the gondola will be enhanced to avoid the risk of occupational injuries. The proposed stabilization system consists of three subsystems, which include a detection system, stabilization system, and final positioning system, see Figure 68.

1. Detection system: The subsystem fitted with two DOF actuators, with two linear actuators supplying translational movement along the X and Y-axes, is equipped with a

limit switch at the Y-axis edge. The subsystem is fitted on the gondola bannister, which can be adjusted horizontally.

2. Localization system: the subsystem consists of five rotational servo actuators that are positioned at the end, middle, and the tip of the robotic limbs. The clamping devices are fitted at the tip of the final link. There is a pressure sensor and a heavy-duty vacuum suction cup equipped in the space between the two clamps.
3. Final positioning system: this subsystem consists of two retractable vacuum suction cups, which secure the robot to the final position. The longitudinal arms are attached to the gondola bannister and can be readjusted horizontally according to the façade dimensions.

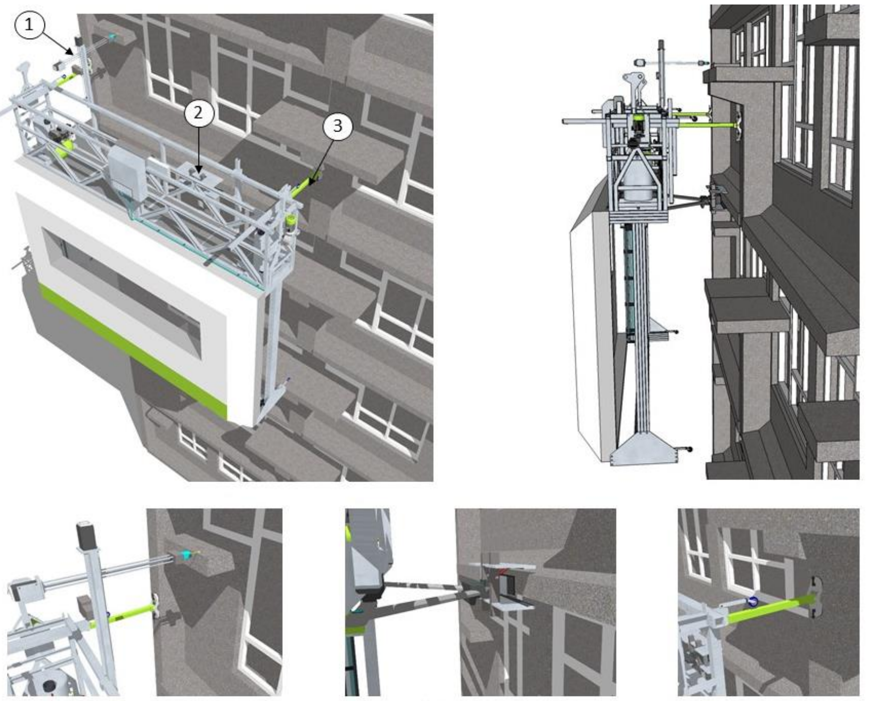


Figure 68: The design concept of the stabilization system.

The localization process can be divided into six steps.

Step one: Robot descends along the cable operated by the conventional gondola stepper motor. The PCF is identical for every elevation of the building, which means the distance between the protruding sections and the floor below are the same. The protruding section will be used as a reference for the limit switch. The system will stop descending when the limit switch touches the upper part of the protruding section.

Step two: Due to inertia and external forces, at this moment the system may swing swiftly. The system is designed so that the stabilization system is aligned with the overhanging edge of the PCF. The stabilization system will reach out and press onto the surface of the bottom edge. Once the pressure sensor detects that even force has been distributed across the sensor, the clamping device will retract and form a firm grasp to the edge, while the inner suction cup secures the system in place.

Step three: Once the system is stabilized, the stabilization system detects if the position is horizontally aligned with the PCF façade, if it is not, then the system will correct the position by using the impedance control method.

Step four: The robot extends the retractable vacuum grippers toward the wall at the proper length, and then grasps the wall to fix it into the final position.

Step five: The robot will detect any deviation between the real and ideal position. If there is any deviation, the system will pause, and steps three and four will be repeated.

Step six: After the painting is complete, the vacuum suction cups and clamps will be unfastened. At this time, the system is ready to descend to the lower floor levels.

To be able to achieve the aforementioned process, a number of controllers should be developed, which are based on the type of interaction between the robot and the building façade. Initially, the robot would need two types of controllers: a position controller and a force controller. The purpose of the position controller is to guide the localization clamping devices to the correct docking position, then the force controller attempts to determine the pressure across the contact surface that detected by the force sensor to verify even distribution. If the force has been distributed evenly, then it means the position between the clamping devices and the overhanging edge is perfectly horizontal.

As demonstrated in Figure 69, the objective of the stabilization system is to detect the correct docking position and the clamping devices to adjust the robot into a horizontal posture. The author has initiated the hardware development work and collaborated closely with Dr. Rui Li from the Chair of Robotics, Artificial Intelligence, and Real-time Systems at TUM in order to jointly develop the appropriate control laws. As a result, two control laws are proposed to solve these tasks.

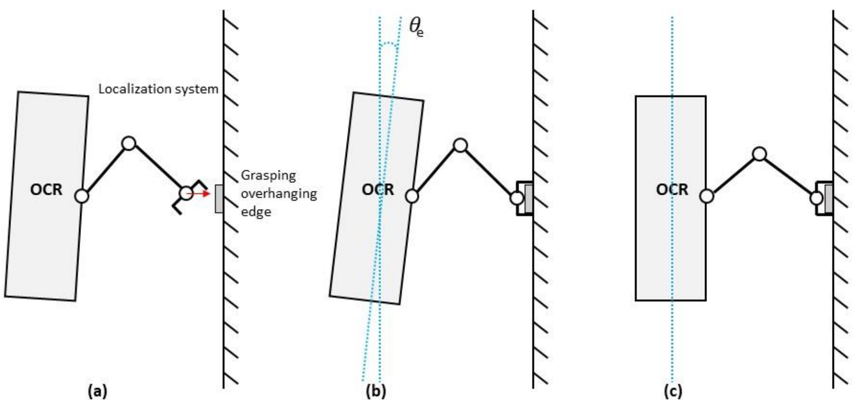


Figure 69: A simple graphic representation of the operational principle for the stabilization system, based on (Rui Li).

1. The proportional-derivative (PD) control law:

In this case, the servo actuators equipped in the localization system act as springs and dampers, which monitor the changes in the kinematic states of the system trajectory (Tan, Liu and Turk, 2011). The PD control method is to be considered applicable to compute the required control algorithm. The dynamics of the robot system can be described in the form of the equation below:

$$M(\theta)\ddot{\theta} + C(\theta, \dot{\theta})\dot{\theta} + N(\theta, \dot{\theta}) = \tau, \qquad (1)$$

where $\theta \in \mathbb{R}^n$ is the set of configuration variables for the robot and $\tau \in \mathbb{R}^n$ the torques applied at the joints, and M, C, and N are the inertia, Coriolis and gravity-related matrices, respectively. In practice, the robot is controlled by τ.

Prior to the stabilization process, the system becomes active, and after the clamping devices hold the overhanging edge firmly, the system should remain in high precision for the movement or keep itself still. This could be achieved with the PD controller:

$$\tau = -K_v\dot{e} - K_p e, \qquad (2)$$

where $e = \theta - \theta_d$, and θ_d define the desired configuration of the robot. K_v and K_p are positive definite matrices indicating the coefficients of the PD controller. For the second-order systems, the relationship between K_v, K_p and the damping D of the system can be described as

$$D = \frac{K_d}{2\sqrt{K_p}}, \qquad (3)$$

It helps to provide an initial value to adjust the expected response of the system.

2. The impedance control law:

The stabilization task requires interactions between the localization system and the overhanging edge of the PCF. To achieve system stability, it is necessary to consider the relative relationships of the environment with which the system will interact. The proposed approach enables the clamping devices to establish a firm connection with the surface and uses a compliant control method to prevent movement caused by external forces. In addition, it prevents direct impact or collision between the system and the surface. The PD controller only provides the target orientation and directs the system to follow the desired motion trajectory. The ideal controller should provide a compliant force in the task space that avoids harsh system collision when contact is made (Lange *et al.*, 2012). The proposed system dynamics behaviour can be illustrated as

$$M_x(\theta)\ddot{x} + C_x(\theta, \dot{\theta})\dot{x} + N_x(\theta, \dot{\theta}) = J^{-\top}\tau + F_a, \qquad (4)$$

Where x is the orientation of the end-effector in task space, J is the Jacobian and F_a is the external force applied to the end-effector. The postscript of M_x, C_x, and N_x indicates that the matrix is an equivalent of the matrix expressed in the task space with

$$M_x(\theta) = J^{-\top} M(\theta) J^{-1} \quad (5)$$
$$C_x(\theta, \dot{\theta}) = J^{-\top} C(\theta, \dot{\theta}) J^{-1} - M_x(\theta) \dot{J} J_a^{-1} \quad (6)$$
$$N_x(\theta, \dot{\theta}) = J^{-\top} N(\theta, \dot{\theta}). \quad (7)$$

Still, the robot is controlled by τ:

$$\tau = J^{\top}(\theta)\big[M_x(\theta)\ddot{x} + C_x\big(\theta, \dot{\theta}\big)\dot{x} + N_x\big(\theta, \dot{\theta}\big) - F_a\big]. \quad (8)$$

Then the desired acceleration trajectory $\ddot{x} = a$ can be designed in the task space. Regarding the contact force, a dynamic impedance model can be expressed as

$$M_d(\ddot{x} - \ddot{x_d}) + D_d(\dot{x} - \dot{x_d}) + K_d(x - x_d) = F_a, \quad (9)$$

where $x_d(t)$ and $x(t)$ are the desired and real motion, respectively. M_d, D_d, and K_d are the desired inertia, damping and stiffness coefficients, respectively. In this case, if a soft and compliant contact is desired, it can be achieved by choosing

$$a = \ddot{x}_d + M_d^{-1}[D_d(\dot{x}_d - \dot{x}) + K_d(x_d - x) + F_a]. \quad (10)$$

Substituting Eq. (8) into Eq. (10), there will be

$$\begin{aligned}\tau = M(\theta)J^{-1}(\theta)\big\{\ddot{x}_d - \dot{J}(\theta)\dot{\theta} \\ + M_d^{-1}[D_d(\dot{x}_d - \dot{x}) + K_d(x_d - x)] \\ + C(\theta, \dot{\theta})\dot{\theta} + N(\theta, \dot{\theta}) \\ + J^{\top}(\theta)[M_x(\theta)M_m^{-1} - I]F_a\big\}.\end{aligned} \quad (11)$$

Furthermore, if M_d is chosen as

$$M_d = M_x(\theta) = J^{-\top}(\theta)M(\theta)J^{-1}(\theta), \quad (12)$$

then the control law can be described as

$$\begin{aligned}\tau = M(\theta)J^{-1}(\theta)\big\{\ddot{x}_d - \dot{J}(\theta)\dot{\theta}\big\} + C\big(\theta, \dot{\theta}\big)\dot{\theta} \\ + N\big(\theta, \dot{\theta}\big) \\ + J^{\top}(\theta)[D_m(\dot{x}_d - \dot{x}) \\ + K_m(x_d - x)],\end{aligned} \quad (13)$$

which do not require the contact force F_a feedback anymore. With Eq. (13), the compliant motion, which limits the contact forces at the end-effector, can be achieved.

The simulation is conducted by Dr. Lir Rui collaborated with the author to evaluate the applicability of the localization system design. In this case, ROS is used in conjunction with Gazebo and Matlab. Gazebo is an open-source 3D robotic simulator that has been vastly applied in both research and practical fields. The first simulation process is to produce a robot model that represents the design of the proposed design. Here, the simplified design is produced. Second, the model is presented in .sdf format, and the dimension of the system as well as the respective inertia properties are used as a reference value in the computer-aided design (CAD) application. Finally, the joint commands are sent to the simulator by using a Gazebo plugin. Within the Gazebo plugin, the controller is designed by using Matlab. The ROS communication mechanism provides the current joints data to Matlab, which determines the joint properties and transfers the data to Gazebo, to then achieve the final movement.

The simulation validated the system control logic, and the result proves the concept is achievable. However, additional work is required to finalize the concept to a practical application.

The framework structure of the simulation task can be described as below, see Figure 70:

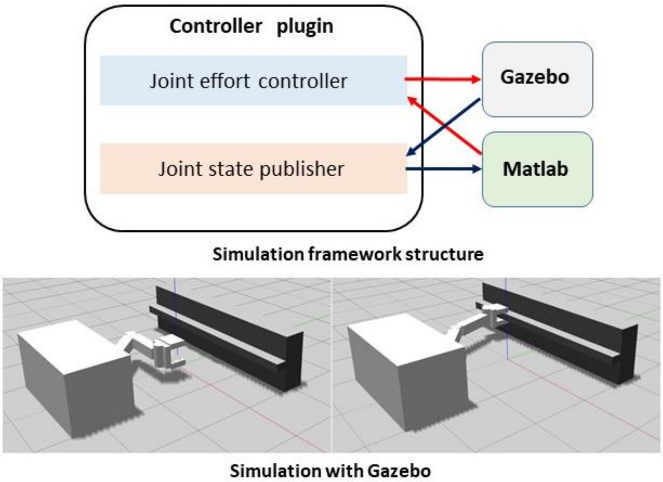


Figure 70: Simulation task framework structure and simulation, based on (Rui Li).

3.7.2 Image segmentation via Deep Learning

Building façade detection and recognition is one of the critical tasks when developing automation and robotics system designed for building façade tasks more generally. As mentioned in earlier sections, the first generation of OCR of the CIC project will be focused on PCF painting tasks. In this section, a speedy and reliable method to assist the OCR making sense of the physical world will be demonstrated. At the time of writing, this method was developed merely as a PoC but could be further developed in the later phases of the project with sufficient funding and testing facilities.

In general, building façade analysis is very challenging because of the complex geometry, design, finishing, and environment. The objectives of the proposed PCF detection and recognition are understanding the location on the openings, such as windows or doors, and differentiating between solid walls and windows, as well as the system adjusting to variations in the design. There are two approaches available. The first scenario is relying on the physical building data, such as the dimensions and positions of the windows, from the BIM model. The BIM model inputs, however, are not as accurate as the OCR would need for operational programming. And, when the OCR is later assigned to a different building with a different design, new BIM data would have to be inserted and the OCR would have to be recalibrated, and overall lengthy process because of a significantly increased set up time. The second, and optimal, the scenario is to detect the features of any given façade automatically and to determine the precise real-life situational setup in real-time. One viable approach for automatically detecting windows and other façade objects is to make use of machine learning techniques, or automated building façade segmentation.

Automated building façade segmentation has various methods that were identified during the literature review. One approach, rectilinear parsing of architectural features, uses ground captured images to partition the building model into individual façades. The partitioned results are then used to construct a larger-scale urban dataset (Zhao *et al.*, 2010). Another approach is marking the regular features of the façade as Near Regular Textures, such as windows and then using the algorithm to map out walls and identify windows and other regular features to reconstruct the entire image (Korah and Rasmussen, 2008). One recent approach for tackling the semantic segmentation of building façades is called the three-layered approach. The first layer is created using Recursive Neural Networks (RNN) semantic segmentation merged with object detectors based on a Markov Random Field (MRF) model and finalized by adding the architectural layer (Martinović *et al.*, 2012). Most of the approaches above use live-cameras to capture façade images and machine learning models that have been trained to classify each pixel in the image as belonging to a specific set of classes: windows, balconies, storefronts, and doors. Generate an appropriate algorithm that requires significant knowledge of the building façade and construction method (Liu *et al.*, 2017).

Deep Learning – a subset of machine learning where the learned models that classify given images are created by neural networks as opposed to more classical machine learning classification approaches such as support vector machines, logistic regressions, or random decision forests – was utilised to perform the image semantic segmentation (Long, J et al., 2015). The initial concept was jointly developed by the author and Dr. Corey O'Meara. because the proposed OCR is positioned in close proximity to the PCF, ground-based imagery may not be appropriate due to the camera angle and other distortions. Nevertheless, ground imagery offers primary learning material for system training.

The approach described in this section used Python 3.6 with libraries NumPy, Pandas, Keras and Tensorflow. As is typical in a machine learning approach (Müller and Guido, 2015), the workflow of training and using a machine learning model follows Table 48:

Table 48: Machine learning training workflow.

Machine learning training workflow	
1	Create and train/test data split of image data including pixel labels
2	Create a neural network model
3	Run the neural network model on the training data and labels
4	Perform a prediction by running the trained model on the unseen test data

Create and train/test data split of image data including pixel labels:

For step number one, only a handful of hand labelled images were used, as can be seen in Figure 71. The image shows the façade panel as well as its corresponding paired pixel labelled in colour.

Since the neural networks require hundreds to thousands of images to automatically learn attributes such as angles, patterns, lines, and colours, the mapped labels are identified in the coloured pixel image (in this case, “window” and “not a window”). Improvements are needed for the initial training dataset by using typical image augmentation methods included in the Keras library.

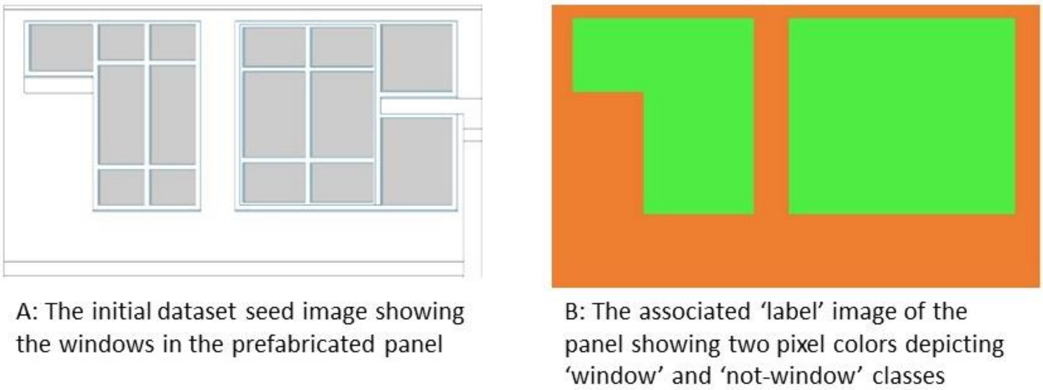


Figure 71: Train and test data with the façade image with pixel labels.

The augmentation technique allows skewness, dimension compression, loss of pixels, and/or gaussian noise to be added to the existing images as different colours. Some examples of this artificially created training data are given in Figure 72.

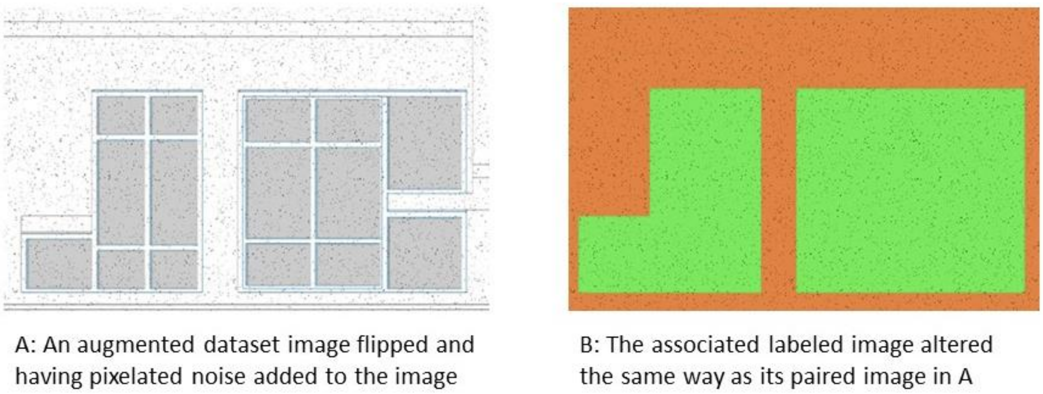


Figure 72: Artificially created training data.

From the single original image, 500 newly generated images were created, all of which are different. However, the same pattern occurs in that the edges of the window are always correctly matched to the colouring in the labelled image pairs. This is of key importance to the concept of using image neural networks. It is exactly these fundamental ‘features’ of the input images that shall be learned by the network so a large dataset of variable images is crucial. Upon creating this data, the full dataset was divided into 80% training data and 20% test data. The training data will be ‘shown’ to the neural network hundreds of times in order for the algorithm to learn and extract the pattern of what is or is not part of a window. Then, for testing the accuracy of the model and seeing how well it predicts on genuine new data, the network was run on the images which were held out from training (a concept known as 'validation'). Sample output of the training can be seen in Figure 73 where we see the time taken to pass 400 images (80% of 500) to the network during training. During this first pass of the data (called Epoch 1) and upon completion of this pass, the validation (test) data is run through it and an accuracy is calculated in terms of the percentage of pixels that are correctly labelled as being a window or a non-window (val. acc. = 20.96%). It is clear, even after the second pass of the data, the validation accuracy jumps to 84.9%, indicating that the neural network is correctly learning the desired features.

```
 1/10 [==>...........................] - ETA: 7:20 - loss: 4.4586 - acc: 0.5484
 2/10 [=====>........................] - ETA: 6:31 - loss: 4.8757 - acc: 0.5870
 3/10 [========>.....................] - ETA: 5:42 - loss: 6.3001 - acc: 0.5036
 4/10 [===========>..................] - ETA: 4:52 - loss: 6.2478 - acc: 0.5274
 5/10 [==============>...............] - ETA: 4:03 - loss: 5.9758 - acc: 0.5540
 6/10 [=================>............] - ETA: 3:15 - loss: 5.6503 - acc: 0.5790
 7/10 [====================>.........] - ETA: 2:27 - loss: 5.4717 - acc: 0.5483
 8/10 [=======================>......] - ETA: 1:39 - loss: 5.2809 - acc: 0.5696
 9/10 [==========================>...] - ETA: 50s - loss: 5.0609 - acc: 0.5912
10/10 [==============================] - 1396s 140s/step - loss: 4.8164 - acc: 0.6117 - val_loss: 11.8074 - val_acc: 0.2096
Epoch 1/1

 1/10 [==>...........................] - ETA: 7:32 - loss: 10.1079 - acc: 0.2318
 2/10 [=====>........................] - ETA: 6:31 - loss: 6.2573 - acc: 0.4720
 3/10 [========>.....................] - ETA: 5:33 - loss: 5.4880 - acc: 0.4798
 4/10 [===========>..................] - ETA: 4:43 - loss: 4.7938 - acc: 0.5467
 5/10 [==============>...............] - ETA: 3:59 - loss: 4.5812 - acc: 0.4866
 6/10 [=================>............] - ETA: 3:11 - loss: 4.2708 - acc: 0.5380
 7/10 [====================>.........] - ETA: 2:23 - loss: 3.9766 - acc: 0.5778
 8/10 [=======================>......] - ETA: 1:35 - loss: 3.7189 - acc: 0.6105
 9/10 [==========================>...] - ETA: 47s - loss: 3.4883 - acc: 0.6367
10/10 [==============================] - 1395s 139s/step - loss: 3.2537 - acc: 0.6377 - val_loss: 1.8262 - val_acc: 0.8495
```

Figure 73: Sample output of the training result.

Creating the Neural Network Model:

A Fully Convolutional Network (FCN8) mode (Géron, 2019), implemented in Keras to perform image semantic segmentation in a pixel-by-pixel basis, was adopted. This neural network consists of 22 layers of neurons as shown in the simplified image in Figure 74.

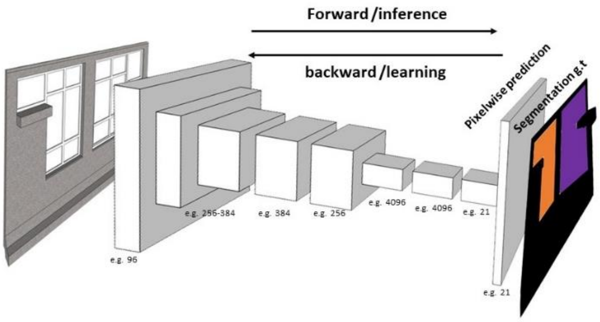


Figure 74: Graphic representation of the semantic segmentation concept, based on (Long, Shelhamer and Darrell, 2015).

The concept behind the FCN neural network which takes as input the full image, then at each neural network layer compresses the pixel information in increasingly smaller intervals until a final pixel-wise prediction occurs in which we predict the class associated to each pixel (Shelhamer, Long and Darrell, 2017).

The general concept behind these ‘convolutional neural networks’, see Figure 75 is that the network gets passed the entire set of training images hundreds of times over while the internal optimisation method attempts to learn the best features of the data so that it can most accurately reconstruct the required (correct) image pixel labelling.

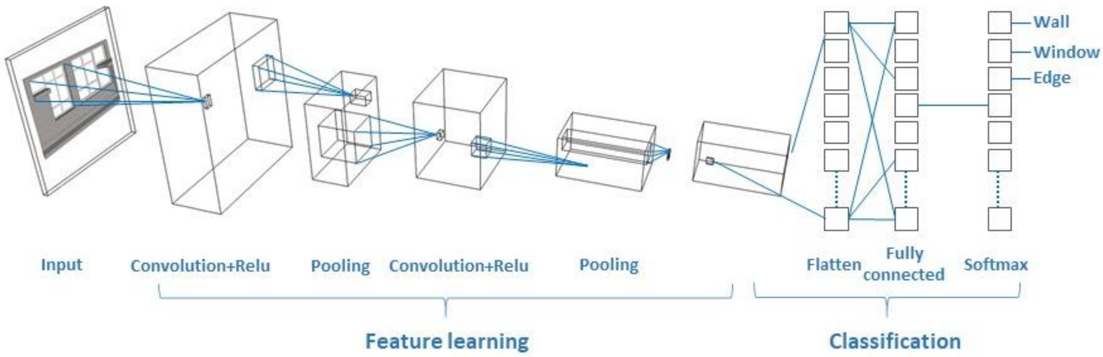


Figure 75: The central concept of convolution neural network for image classification depicting how each swath of pixels in the input image is analysed in order to obtain a classification of the type of image, based on (Saha, 2019).

The main concept of the convolutional neural network is to look at the RGB colour values for each pixel in the input image within a small X by X square viewing size and scan this box across the entire width of the input image. By grouping patterns which occur in the sub-pixel boxes and continuously lower areas of detail, the neural network is able to learn abstract ‘features’ of the image by comparing the required pixel classification as expressed in the paired label image. Starting from an initial image, the first convolution layer is composed of small blocks (neurons) that only ‘look’ at a small square portion of the image and, in particular, analyse the RGB colour vector embedded in those pixels of the image. By applying a ‘pooling’ layer at the next step in the sequential neural network model, it looks at the largest value within a small square area and then uses this value as an output for the next layer; in a sense, it ‘down-samples’ the image while maintaining the important features of the image Figure 76.

The convolutional and pooling layers repeat this process until high-level features and shapes are learned from the input image. At the end of the neural network, a classification component to determine whether or not each pixel of the input image belongs to a certain class was applied (these are sometimes known as ‘labels’).

In addition, the neural network gets passed through the entire set of training images hundreds of times over while the internal optimization method attempts to learn the best features of the data so that it can most accurately reconstruct the required (correct) image pixel labelling.

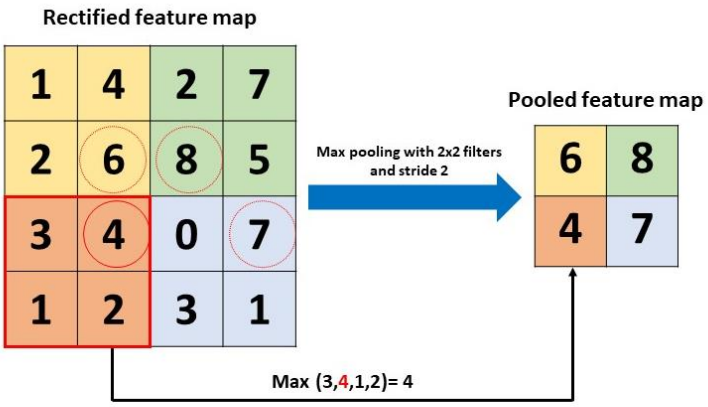


Figure 76: General pooling concept, based on (Sharma and Mehra, 2019).

Preform a prediction by running the trained model on the unseen test data:

Once the neural network has been trained, we are able to give the network the new test images, both those that were held out from the full data set as well as completely new test images, in order to see how well the machine learning algorithm learned the desired classifications. Some of the preliminary results are shown in Figure 77 below. The upper left image from the test shows the colouring of the window edges due to the learned edge features from the training dataset. The remaining 3 images are other instances of the panel (both 3D and actual construction site images) where we can see the basic window outline and shapes have been (for the majority of close cases) correctly identified even at extreme viewing angles. Furthermore, the colouring overlay of boundaries of the windows and window edges are clear. Although not perfect on a pixel-by-pixel basis, additional post-processing can be done to smooth out the lines to obtain bounding boxes and filling-in areas where there are discontinuous pixel window labels. The training results verified the proposed approach is viable and that the system can detect the position of the window from the input image.

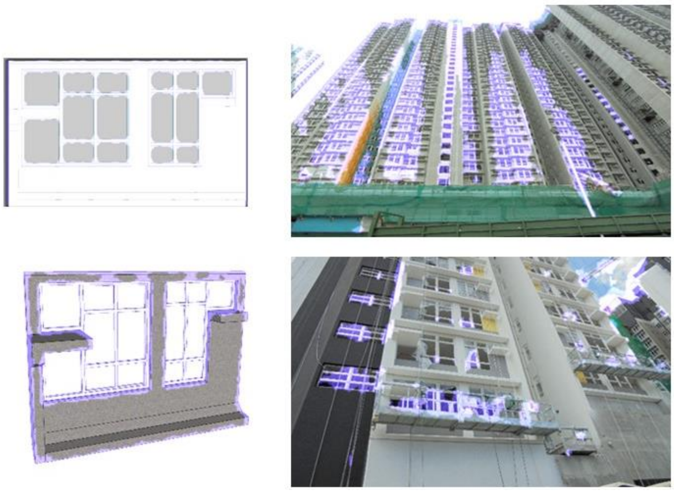


Figure 77: The preliminary results.

3.7.3 Process information modelling (PIM) concept

Due to the complex nature of the construction project, fragmentation of the industry, diversified stakeholders, and different means of data technologies makes managing heterogeneous data extremely difficult. This is more evident when implementing OCR; data management becomes intensified, and more challenging to integrate with the existing data. Therefore, to successfully implement OCR, the next-generation data management tool is needed not just for gathering information or use of several technical tools but also managing information across diverse collaboration and interrelationship of the key stakeholders in real-time, yet with consideration of data required or generated by OCR. Additionally, it is essential to deliver the right information to the right place for the right people at the right time (Jernigan, 2008). In this section, the author introduces the PIM concept, the relevant background research, the principle of the concept, the case study building and the proposed OCR as an example to validate the applicability and potential of the concept. At the time of this writing, PIM has been developed only as a conceptual model that demonstrates the overall concept, yet it is capable of offering basic instructions and data analysis that is based on the scenario created by the Hong Kong CIC project. The PIM concept featured in this section is the revised version of the paper that has been published in the proceedings of the Creative Construction Conference 2018 (Pan, Langosch and Bock, 2017).

First, as part of the background research, the author analysed the most popular trend in data management in the construction industry. BIM is one of the most promising developments and is most popular in the architecture, engineering and other industries (Higgin and Jessop, 2013). BIM became more influential within construction projects, which commonly are used for the design, visualization, planning, facilities management and cost estimating purposes. Using modern modelling tools, such as Revit Architecture, ArchiCAD or Tekla Structures, the content produced by architects, designers and engineers have evolved from traditional 2D-drawings, sketches and written specifications to parametric, object-oriented 3D-models embedded with information to describe any building or facility in detail (Pan, Langosch and Bock, 2017). When the data has been integrated efficiently, the computer-generated model contains precise geometry and relevant data necessary to support the construction, fabrication and procurement activities involved in the project (Eastman and Sacks, 2008). This is particularly relevant to the implementation of the proposed OCR, yet exposes the limitations of the existing BIM technologies. For example, the design building can be inputted into the system to assist the engineers in understanding the geometry of the building. On the other hand, proactive data management can benefit the overall workflow. To be specific, the data can be used for system pre-calibration to ensure correct system setup. The data related to logistics can inform the labour staff with a clear time when the system will arrive on-site. During operation, the real-time data can confirm if the work is on schedule, whether the consumables need to be replenished, and the data regarding the stocks availability of materials from the suppliers. However, the existing BIM technologies are underequipped for such task, and the next section explores the reason.

The widespread use of digital technologies will lead to huge amounts of data being generated throughout the construction process. In each step of the construction process, the project team deals with a specific type of datasets; the data is often required to make critical decisions. The conventional BIM technologies can manage multi-dimensional CAD information systematically, and improve cross-disciplinary collaboration. However, BIM technologies are often fragmented in the construction project, because of various levels of data understanding amongst the stakeholder. The outcome of implementing BIM hugely depends on the familiarity, experience and professional background of the parties that handle the data. Furthermore, BIM application is a knowledge-based and object-oriented approach that aims to digitally and visually represent real-world situations. It can be considered as the identical twin of the real world. This might sound unrivalled. However, when implementing construction robots or carrying out a complex construction project, understanding only the real world condition is not enough (Harty et al., 2010). A know-how based, interactive, proactive and responsive extension of BIM is required (Jernigan, 2008). Hence, the PIM concept is introduced, which aims to integrate BIM for extensible solutions with a process-based database platform, which allows for smooth real-time data transfer and supports continuous data sharing among all stakeholders (Pan, Langosch and Bock, 2017).

In principle, PIM consists of five fundamental stages, which include Project break down, Data management, PIM Big Data (PBD) architecture construction, Implementation, and PBD distribution. During the Project break down, each project stage is formulated as an individual data cluster, which can be deployed, assessed, processed and transferred independently, see Figure 78. For example, the initial data clusters consist of design data, production data, procurement and tendering data, logistics data, OCR operational data and lifecycle management data. Thus, the data clusters are loosely coupled and provide the database information that can be categorised, classified and shared with the relevant parties. The human data, physical data, project management data, facility data and cyber data are analysed and integrated. The main goal of this stage is to differentiate and integrate the data based on the relevance of the information that is evaluated by the key stakeholders. This provides positive implications on interdepartmental, cross-functional and cross-disciplinary data interaction; therefore, it adds value throughout the project (Pan, Ilhan and Bock, 2018).

In the next stage, PBD is further categorised into four main databases, which are the physical database, BIM database, Internet of Building Things (IoBT) database and maintenance management database. The physical database contains the information that is gathered through hardcopy documents, verbally interacted as well as the information not yet converted into digital data (Pan, Ilhan and Bock, 2018).

The IoBT database comprises a range of smart data collected throughout the construction phases, which include geolocation tracking, monitoring of equipment, inventory, procurement management, quality inspection, real-time measuring and control and remote operation. The maintenance management database covers the information accumulated over repair, alteration, conversion, upgrading, scheduling, and budgeting of the lifecycle management activities (Pistorius, 2017).

All data mentioned earlier is collected and stored in the PIM data Processing Unit (PPU). The main strategy of PPU is to process, integrate, transfer, share and store the real-time data. In addition, it enhances collaboration and supports decision-making activities. PPU is not only for data acquisition, but also and most importantly, it is a range of interoperable applications that actively process data in real-time and analyse huge amounts of data created from a variety of sources (Pan, Ilhan and Bock, 2018).

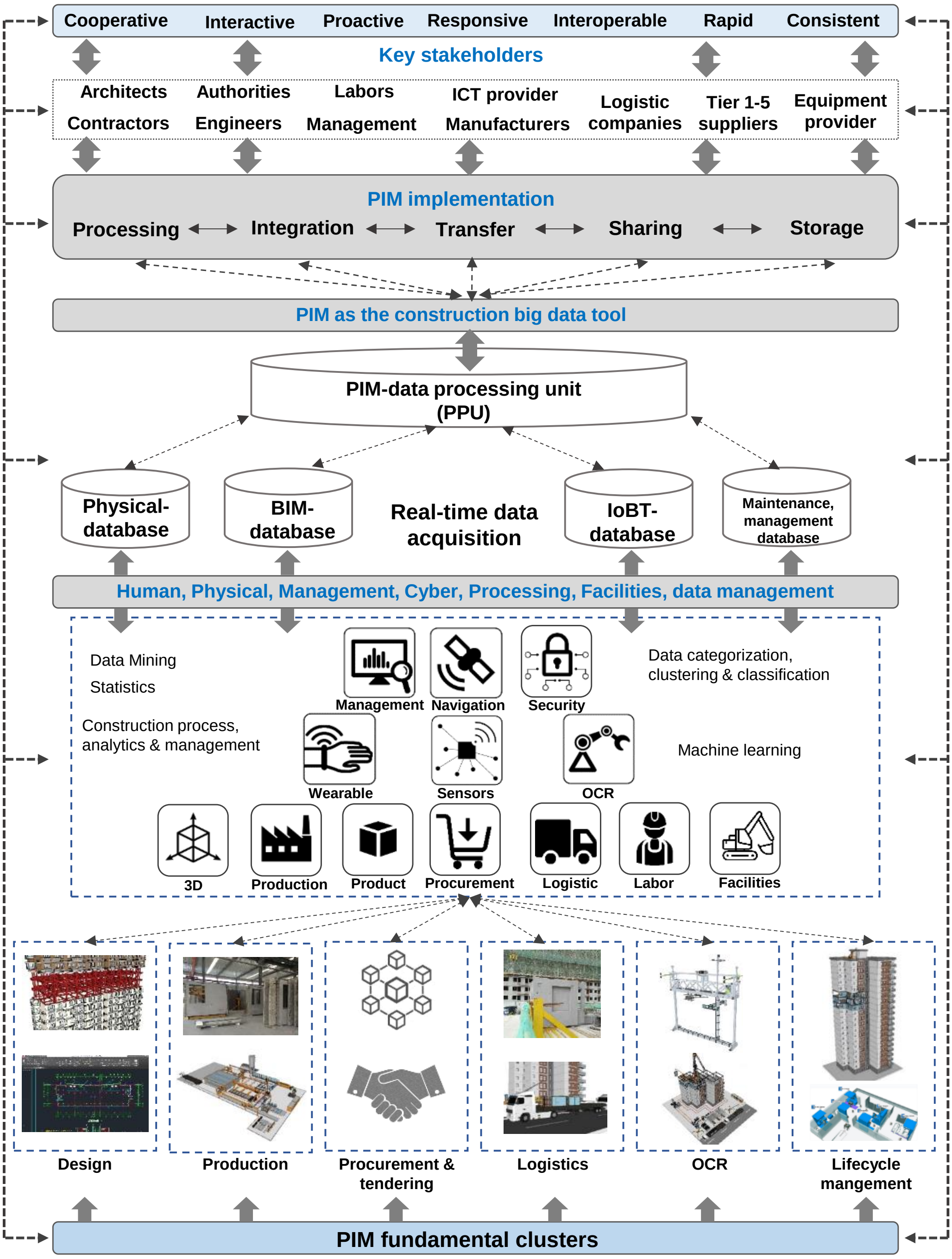


Figure 78: Process information modelling concept, based on (Pan, Ilhan and Bock, 2018).

The author conducted a literature review to seek theoretical background, which validates the PIM concept. The topics considered relevant to PIM development are Big Data Engineering (BDE), Big Data Analytics (BDA). Theoretically speaking, PIM can be perceived as a Big Data application specifically developed for the construction industry. In general, Big Data is used to accumulate various types of data then process them with other data analytic tools such as Apache Hadoop (AH), Apache Spark (AS), and Starfish. They are capable to deal with large nodes of heterogeneous data with high processing speed and operate under high-level programming languages such as Python, Java, R and Scala (Zaharia *et al.*, 2016), (White, 2012), (Miller *et al.*, 2016).

There are various examples in computer software design which offer conceptual principles similar to those in PIM, such as Service-oriented architecture (SOA), Microservice architecture, Service discovery or service discovery protocols (SDP). A brief analysis is conducted to offer a reinterpretation of the PIM concept by using software programming concepts (Pan, Langosch and Bock, 2017).

SOA can be described as a loosely coupled program architecture designed specifically to meet the needs of an organisation (Arsanjani, 2004). SOA is independent and self-contained, yet when combined with other software it forms the functionality of a large software application. The unit architecture and information clusters in PIM also share similarities with the service architecture in SOA (Zaharia *et al.*, 2016).

Microservices is inspired by SOA, which provides groups of independent program components that are operated and deployed separately, yet are based on precise protocols and dedicated memories. It has the potential to contribute to the development of the PIM concept. However, there is limited research that has been conducted that emphasised the topic (Nwana, 1996). Therefore, further validation through application use-case is necessary (Dragoni *et al.*, 2017).

SDP has emerged from the recent development of ubiquitous computing (Golden G and M, 2001). It allows the system to detect services that are embedded in any cluster or node of the network. In this case, services can also be considered as anomalies. Service discovery is the action of finding a service provider for requested service (Czerwinski *et al.*, 1999). Service discovery can potentially operate as a search engine for PIM architecture (Pan, Langosch and Bock, 2017).

The author discovered some existing applications that have been applied in other industries, which can stimulate future PIM development. One is a solution developed by Actyx® and a novel technique developed by the German Space Operation Center (GSOC). Actyx® is a company based in Munich, which offers extensive ranges of software applications aimed to increase productivity, seamless integration, reduce lead-time, and identify bottlenecks in various industries. There are some applications and products the company offers that seem to share the same objectives as PIM. For example, Actyx® Material Movement Logging is an application for the manufacturing industry that offers transparent, accurate and practical logging of the material logistic flow in the warehouse. This function is similar to logistic tracking and documentation described in PIM. The aforementioned applications demonstrate similar objects as the proposed PIM concept; however, they are not available for the construction industry. In order to implement them, the application needs to be customised, which might be a costly task (Actyx, 2019), (Pan, Langosch and Bock, 2017). GSOC developed an innovative technique in machine learning and modular data analysis framework, called Automated Telemetry Health Monitoring System (ATHMoS). The principle of ATHMos is to train the system to learn the correct historic data or on-going mission lifetime data, and then to automatically detect and analyse new telemetry data as well as identify anomalies. The big data and machine learning technologies have only been adopted in the space operation sector (O'Meara, Schlag and Wickler, 2018). ATHMoS provides insight on how to apply deep learning and Artificial Intelligence in the construction industry, which is particularly beneficial when the construction industry progressively implements OCR.

The author uses the case study building to investigate how to implement a PIM application to carry out the external façade painting task by using the proposed OCR. During this research task, the author worked closely with Dr. Bahriye Ilhan; together the project team proposed a method to simulate the basic concept of PIM by using the existing data of the case study building and formulating an analysis through Industry Foundation Classes file (IFC), and IFC File Analyzer (IFA). The data management process consists of several steps. The first step is to conduct stakeholder analysis and to formulate a detailed data-oriented work task breakdown of the working process, see Figure 79. Second, to construct the case study building with BIM application, in this case, ARCHICAD is used. Third, system data such as the properties of PaintingRobot, PaintingMaterial, and MaxHeight are generated. Then data types for the criteria are set as IfcBoolean, IfcPropertyEnumeratedValue, and IfcReal, respectively. The system determines if a robot performs the façade painting or not, wherein MaxHeight refers to the maximum height of the façade and PaintingMaterial contains the paint information. The CIC template file, see Figure 80 including the extended properties and building materials for façade painting is created. The user should assign each property using the IFC Manager menu. Pset_CIC_Painting data is applicable to the project entity. Then, the BIM file is exported as IFC format and transferred to an Excel file via IFC File Analyzer (IFA) (Lipman, 2017).

This method validates one of the key functions of PIM, in which if the correspondence task is being TRUE, the relevant data for the complementary process can be extracted and distributed to the correct recipient. For instance, to check the supplier of the paint automatically and in case of unavailability of that supplier, searching the possible suppliers via warning the related parties, consequently to avoid project delay.

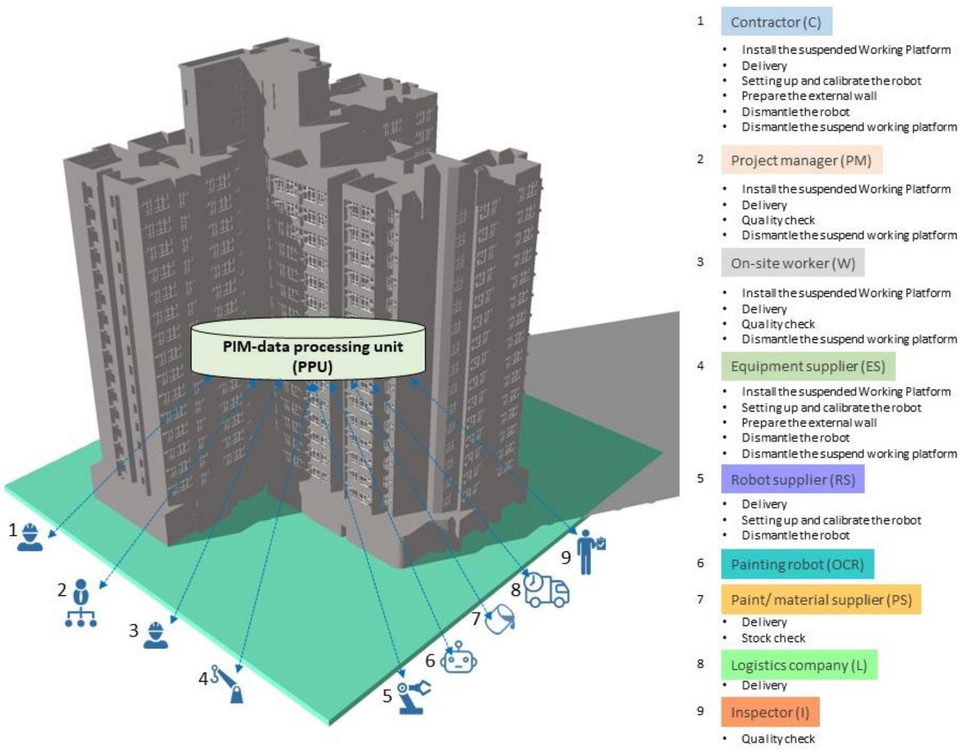


Figure 79: Stakeholders and their dedicated tasks.

At the time of this writing, PIM is only developed as a conceptual idea that establishes the overall concept, yet will not bear on its ability to offer basic documentation tasks or providing instructions and data analysis by using existing Microsoft Excel tool. The concept requires further R&D effort through extensive real case study and testing to develop the concept further (Pan, Ilhan and Bock, 2018).

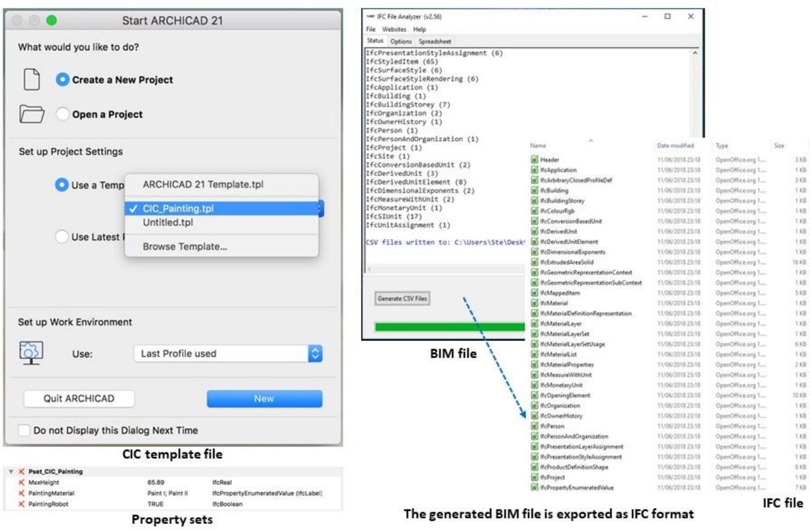


Figure 80: The CIC template file and exported IFC files, based on (Pan, Ilhan and Bock, 2018).

3.8 System development process and iteration planning

Product development processes (PDPs) is a critical activity that refers to the company bringing a new product to the market or improving an existing product then relaunching it to suit the changes of market demand, stand out from the competition and to satisfy the requirement of the customer. PDPs identify what to develop, define the concept and planning of the detailed actions, evaluates a product by testing, and finally releases the product on the market. Undoubtedly, PDPs plays an important role in the success of OCR development. However, OCR bears special circumstances that require an alternative approach as opposed to the standard consumer products.

Construction robot serves a complex industry, as mentioned in the previous chapters, which involves a wide range of stakeholders or participants, and each one possesses a unique stake. Meanwhile, the construction industry is influenced by regulations, policies, demand, and the economy. More importantly, these factors can influence stakeholder's expectations or involvements in the construction industry, hence, ultimately shaping the decision-making process. Consequently, the OCR needs to be developed to address the changes in the market, stakeholder's requirements, to stand out from the crowd, and adopt other external influences. In terms of OCR, by definition, the best design does not exist indefinitely, only the best design in a giving time that is designed for a specific task. Therefore, it is an incremental process rather than an impulsive action. It is clear that product iteration is inevitable and it is an important step to secure the critical competitive edge of an OCR over the competitors. Iteration can occur after the product has been finalized and/or commercialized, and it can happen during the development phase. OCR often consists of groups of rather complex, interconnected hardware and software components. It is very challenging for the product developer to decide which part of the product should be developed or iterated first, or when to add a function to the existing system to improve the overall performance.

The most popular method used for PDP is the waterfall method (Erdogmus and Williams, 2003). The attribute of the waterfall method follows overlapping research steps that aim to identify product specifications early in the development phase. The advantage of the method is to narrow down decisions by forming clear research direction early on. The early definition of the specifications allow the development team to predicate the time and resources will be consumed through product development as well as mitigate time waste for midstream design alteration (Darian W and Steven D, 2002). The waterfall method performs well when the technology and development cycle of the product is well known, see Figure 81. However, the drawbacks that are imposed by the waterfall method will have a profound implication on OCR development. The firm specification in an early stage will narrow down iteration, which reduces the flexibility of the design. The waterfall method is more rigid in that it cannot incorporate feedbacks throughout the development phase, especially from the middle or later phase of the development.

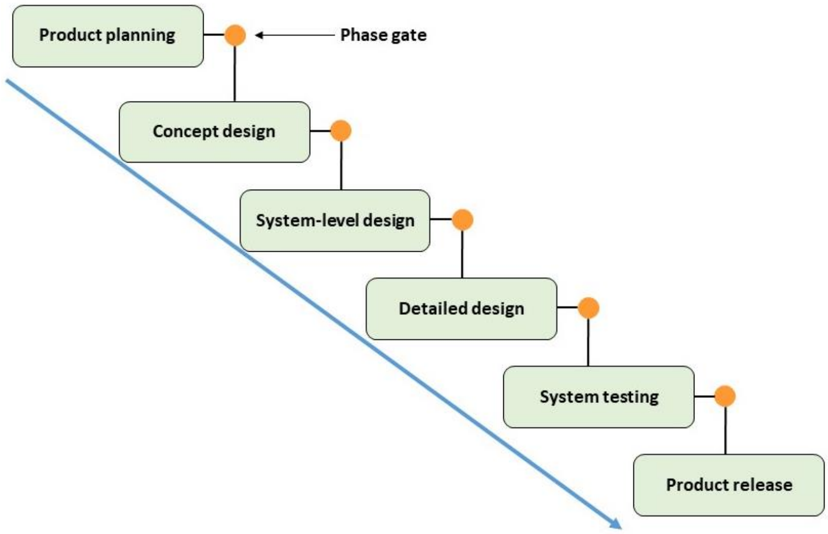


Figure 81: The traditional waterfall product development process, based on (Darian W and Steven D, 2002).

In terms of OCR, very often, in the early stage of design, the design team is not able to specify everything due to a limited understanding regarding functional and non-functional requirements, allocation of function, and the levels of automation of a specific construction task. As mentioned earlier, this is an incremental process; hence, the design specification will change over time in order to address perpetual changes from the evolving market or technology. As a result, the typologies associated with the waterfall method is not compatible with OCR development. This is due to that OCR serves a dynamic market, in which profuse with uncertainties, therefore OCR PDPs need to acquire maximum flexibility for system upscale and iteration.

There are few modified waterfall methods that have been studied, and the author would like to compare them with the classic waterfall method to decide which one is more relevant and to be adopted for OCR development.

The first one is very similar to the standard waterfall method. The method introduces a number of overlapping stages, which embrace continuity of development to allow decisions to pass on to the next stage and to encourage cross-boundary integration of feedbacks, knowledge, and teams. There is a phase-gate (PG) in between each step to allow the design to review what has been done in the previous step, and what should be carried out in the next step. The disadvantage of this overlapping version of the waterfall method is also shared with the standard waterfall method, which is the method that is restricted to parallel steps. Again, PDPs of OCR contains many interdependent steps, and not knowing the relationships between each development steps could lead to unforeseen interdependencies, with vague requirements that lead to misleading specifications (Biazzo, 2009). For example, a design decision has been made during the conceptual step, which was validated during the system-level design step, yet during the system testing step, an issue occurs that requires system alteration and potentially pushes the system design activity back into the system-design step. In this case, due to the parallel method, the design team is unable to predicate the incident that would happen in the later step, thus this will cause a delay as well as rework. To make the situation worse, due to unpredictability, the systems have been designed without the flexibility to be altered in the later development stage, which means the product has to be designed from scratch. Therefore, only by overlapping a parallel method is not adequate for OCR development, see Figure 82.

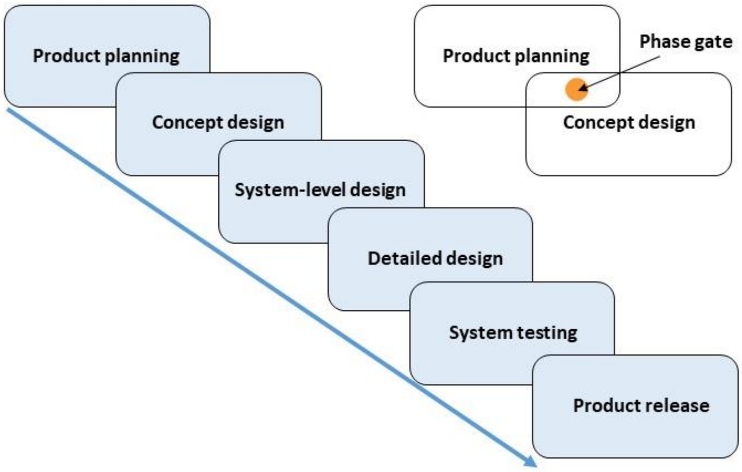


Figure 82: The overlapping waterfall product development process, based on (Darian W and Steven D, 2002).

The spiral PDP is widely adopted in the software industry, which revolves around a comprehensive iteration cycle. It consists of five steps; the first step is a concept design, which determines objectives, alternatives, and constraints. The second step is the system-level design to identify or resolve risks. The third step is the detailed design to evaluate alternatives. The fourth step is an integration that proposes iteration deliverables. The fifth step is further planning to develop the iteration strategy; the spiral continues until the design satisfies the requirements.

One of the biggest advantages of spiral PDPs is that the method allows the designer to predict future processes. This method facilitates an incremental decision-making process that obtains information from each part of the spiral in an early stage. The early product accommodates later changes unlike the parallel method, hence reduces the risk of rework. On the other hand, the spiral process has some limitations. First, the method is more complexed than the waterfall method, which requires additional management efforts. The designer must possess extensive knowledge of the product and understand when to move on to the next step or the next round of the spiral. Second, being unable to define the final specification in an early stage could lead to delay in delivering parts or components that require long lead-time. Therefore, it increases the risk of slowing down the entire production. Finally, the spiral method is considered too excessive when dealing with simple product development. According to other researchers, it is critical to complete the first spiral correctly and to address all necessary objectives and planning alternatives. Some suggest to divide the first spiral into smaller manageable cycles, and to address them separately (Boehm and Bose, 1994). Overall, the spiral method offers a well-planned comprehensive cycle of iterations, see Figure 83. Alternative solutions are prepared prior to the development work entering the next step.

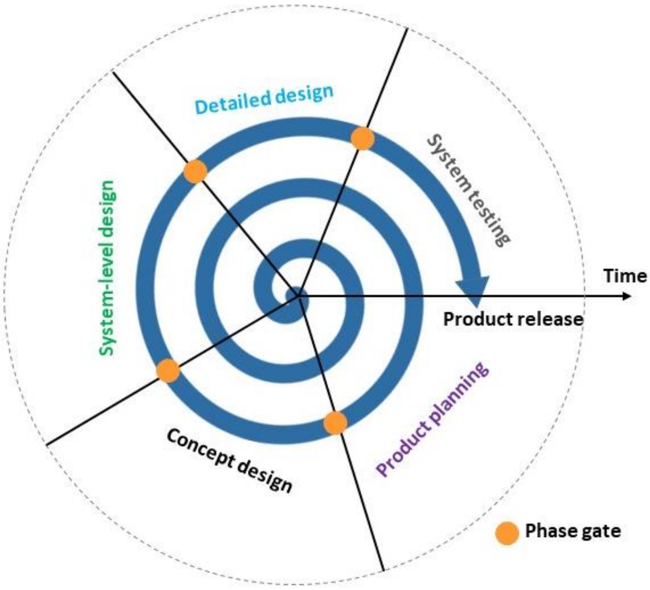


Figure 83: The spiral product development process, based on (Darian W and Steven D, 2002).

The spiral method can be adopted to OCR development; however, OCR consists of many integrated parts and components that are designed to address a diverse range of construction tasks. Even a system with the same function, the design may vary differently depending on the requirements, regulations, physical environment, and budgets. Sometimes, the designer might identify additional requirements after a development stage, and the new requirements have to be conveyed through the product iteration. As a result, the principle concept of the spiral method can be used, yet a more adaptive, interactive, and flexible method is required. One concept has the potential to address the requirements, which is called Agile Product Development (APD).

APD is the latest incremental development methodology that has been adopted in software engineering. In software engineering, the developer tends to separate software into smaller manageable components and then combine them into the complete software (Szyperski, Gruntz and Murer, 2002). It reduces the efforts on developing a comprehensive software, instead of by focusing on specific component customizing incrementally (Stender, 2002). Ultimately, the APD provides a solution that is flexible, transparent, client-centred, incorporative, interactive, and incremental.

Evidently, software development differs from OCR development, yet they share some common grounds as well. As mentioned previously, OCR is more complex than the usual consumer product. It has to offer great flexibility in design to allow the system to iterate over time. To stay competitive in the construction market, OCR has to consider scalability from an early development stage. Once the OCR is altered its function and aims at a different construction task, consequently, this change will impose a huge implication in the system design. Because the system basically performs a different set of skills when tackling a new on-site construction project, it uses different tools, equipment and meets completely new specifications and standards. Therefore, supplementing an incremental development strategy such as APD seems to be befitting.

There are a few examples that feature how APD has been implemented in non-software development contexts. Encouragingly, they have presented rather promising outcomes. These successful cases include SpaceX and Saab Gripen fighter jet from the aerospace industry (Furuhjelm *et al.*, 2017). In the automotive industry, the example of Wikispeed an open-source modular car concept that adopted Agile, lean and Scrum (Gloger, 2016), (WIKISPEED, 2019) features it. As the example indicates, APD can be adopted cross-industry, which lead to a modality in product design that improves overall performance, reduces development risk, and costs. However, when adopting APD many subtasks, stakeholders, and team activities need to be well organized. A good planning strategy is crucial to allow the involved parties to gain a common understanding of the development objective, market demands, business strategy, and the efforts and resources required to accomplish the goal.

A comprehensive Agile planning strategy, named “Iteration Zero”, is proposed by James W Grenning, and it is presented at the Embedded system's conference in Boston in 2013. Iteration Zero has categorized a list of activities that focus on how to manage a team to carry out an entire process of product development iterations. The strategy demonstrates several advantages when comparing to the traditional method. First, the product development plan is continually adjusted and evaluated. Each task has been reinterpreted as simple stories so that it is easy to follow, even if the involved parties lack specific knowledge. Second, Iteration Zero is an adaptive agile planning method that offers an early warning when the development direction has been detected off-track. It allows the product owner to react to potential changes in product design proactively and to prepare solutions in advance (James W, 2012).

When concerning OCR APD, the author proposes an alternative approach that includes predetermined product development stages, namely product planning, concept design, system-level design, detailed design, system testing, and product release. When product development processes from one stage to another, the designer team will go through a PG, and based on the feedback and discussion from the design team, a decision will be made on whether the development is ready to be passed on to the next stage or it need rework, iteration or to be passed back into the previous stages. As shown in Figure 84, sometimes, the decision of iteration can be spanned over several phases of development. This is because of the interconnected relationships between each phase, and the ability to allow the design to be altered during the development is vital to the success of the overall development (Unger and Eppinger, 2011). Figure 85 illustrates a potential OCR APD process. After the product planning stage, the product moves towards the concept design stage. When the conceptual design has completed the product is passed through to the system-level design stage, where some iterations have been made across the previous stages. The altered design then passes to the detailed design stage, based on the feedback from the PG, the product has been pushed back into the system-level design stage for iteration. After the detailed design stage, the product is passed onto the system testing stage, and the testing results suggest some parts of the product has to be redesigned. Consequently, the concept of those inappropriate parts has to be reviewed. Before product release, the product will be finalized through another cycle of iteration by revisiting the detailed design stage to ensure all specifications have complied with the requirements. Effectively, the proposed OCR has implemented the incremental APD approach to ensure that the functional and non-functional requirements identified by the stakeholders in various project phases are fulfilled throughout the product development stage.

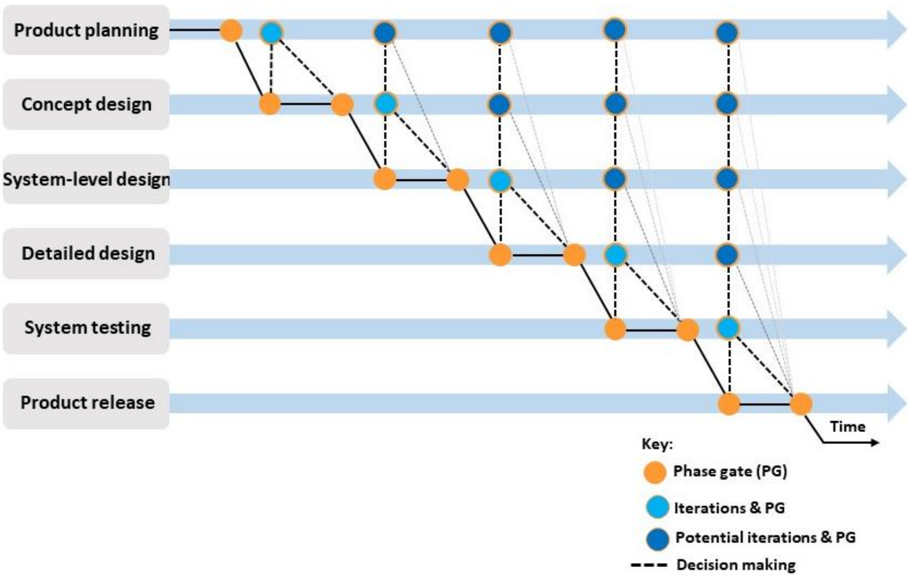


Figure 84: The proposed evolutionary OCR development process.

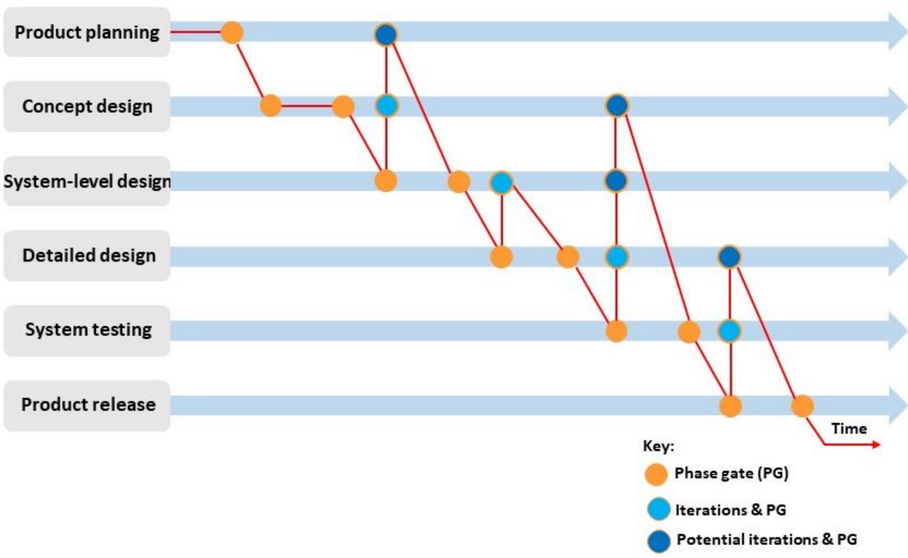


Figure 85: The proposed Agile Product Development process for OCR.

Besides adopting the alternative APD approach, the proposed OCR also exploited a design philosophy called Open-building (OB) concept that is commonly used in the modular building design. The similarities between the modular building and OCR are flexibility, adaptable, and are able to optimize the stakeholder's preferences wherever possible. Also, like the OB concept, the proposed OCR has been designed with a high level of flexibility that demonstrated through the entire product lifecycle (Kendall and Teicher, 2010). The proposed OCR hierarchically categorized the main components of the system based on the predicted lifetime Figure 86. The components with longer lifetime such as the suspended working platform and the supporting frame act as the skeleton, which also determine the main usage of the system. The components with less lifetime such as the stabilization system, end effector, detection system, retractable vacuum cups, and control system can be easily disassembled from the main structure, which is an important feature to allow product upgrading, scale-up, maintenance, and iteration.

In terms of system iteration of the proposed multifunctional façade finishing robot, as mentioned earlier, the first generation robot primarily focuses on external façade painting. The next generation function of the system can be extended to concrete wall grinding, and window water leakage detection, see Figure 87. These two additional functions have been identified by the existing stakeholders to be highly physically demanding and can be enhanced by adopting OCR. Based on the similar platform design, the system application can be expanded into prefabricated building manufacturing, celling painting, and interior painting tasks. Furthermore, this is to further scale up the system application and maximize the benefits of the proposed robot system. Besides the identified applications within the PHC sector, the use-case building types can be extended to office buildings, hotels, public and commercial buildings, factories, and shipyards.

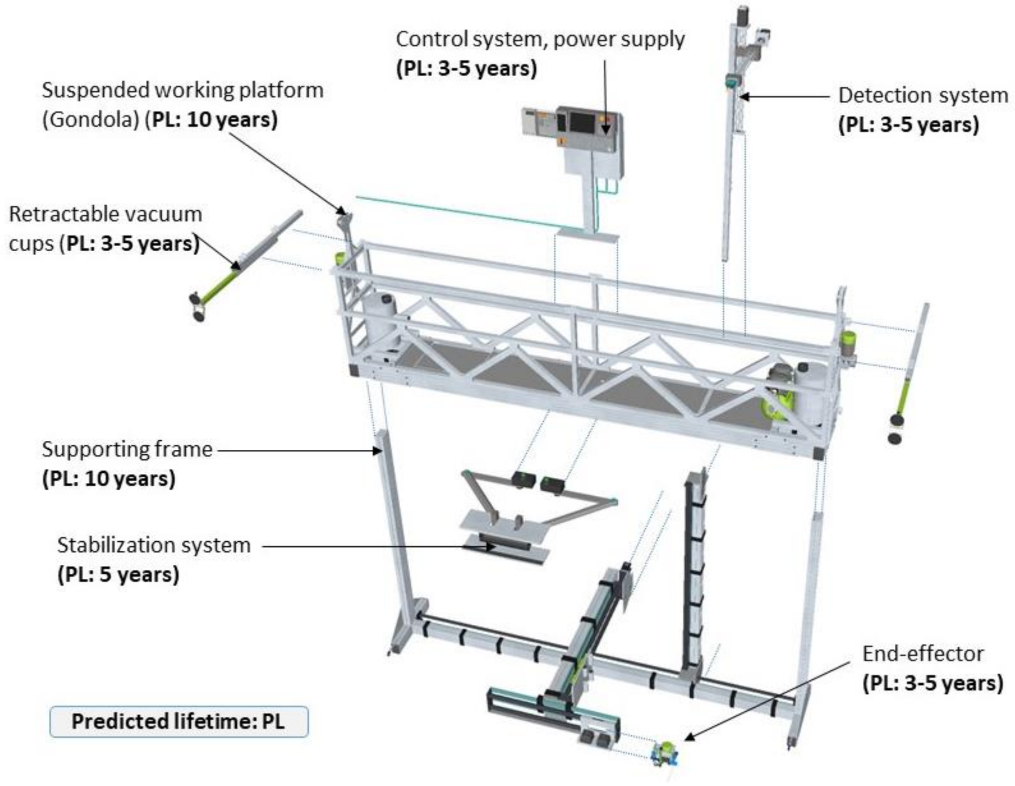


Figure 86: The hierarchy analysis of the proposed OCR.

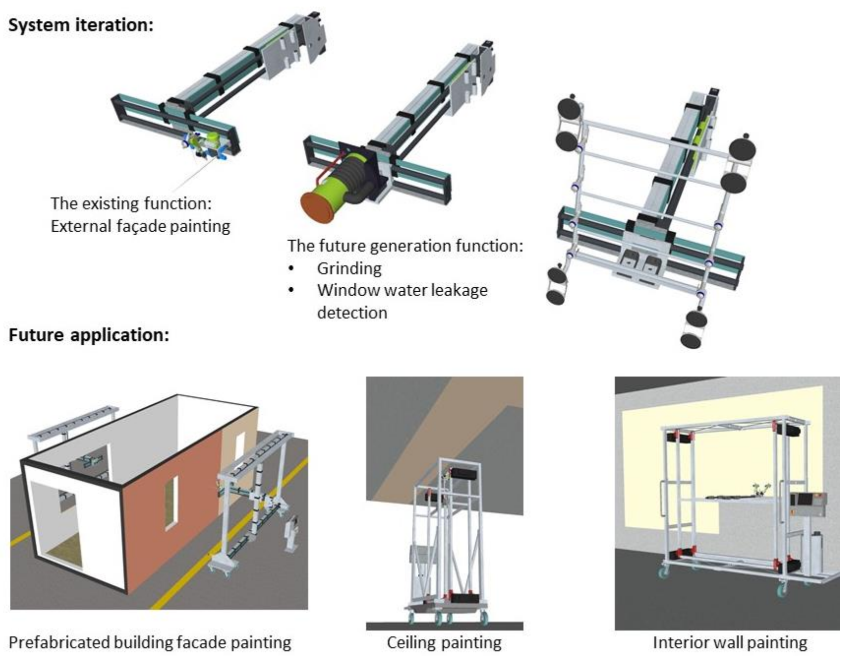


Figure 87: System iteration and potential scalability.

3.9 Conceptual prototyping and Initial dissemination

In many engineering practices, prototyping is an effective method to support design decisions in order to produce tangible objects that demonstrate the potential function of the proposed product. Meanwhile, it is critical for the project in this stage to know how to maximize the impact to the target audiences and to explore the current development result and ensure an efficient dissemination method of the proposed OCR that raise public interests and awareness of the technology. In this section, the author introduces the prototyping activities and demonstrates the initial dissemination activity.

3.9.1 Conceptual prototyping

The type of conceptual prototyping method used in the proposed OCR development includes object-based and computer-based methods. In this case, the object-based method refers to producing physical models. The simple physical model can be very expressive and easy to understand, such as scale models made of plastic or electrical components. The interactive model considers the interaction and integration between components, which provide a basic representation of the fully functional product. The detailed prototype will ensure all parts; components are well integrated according to the final design specification. It will present the majority of the design features, and the function, hardware, and software integration of the system can be tested both under laboratory condition and under on-site condition. As shown in Figure 88, in this phase of the project two types of physical model were produced. The detailed prototype is produced in phase two right before pilot testing.

The computer-based method refers to the static model that is produced by CAD software, such as Sketchup and Autodesk inventor, and the dynamic modelling such as Gazebo. The computer-based static and dynamic method can also be referred to as the digital mock-up design method.

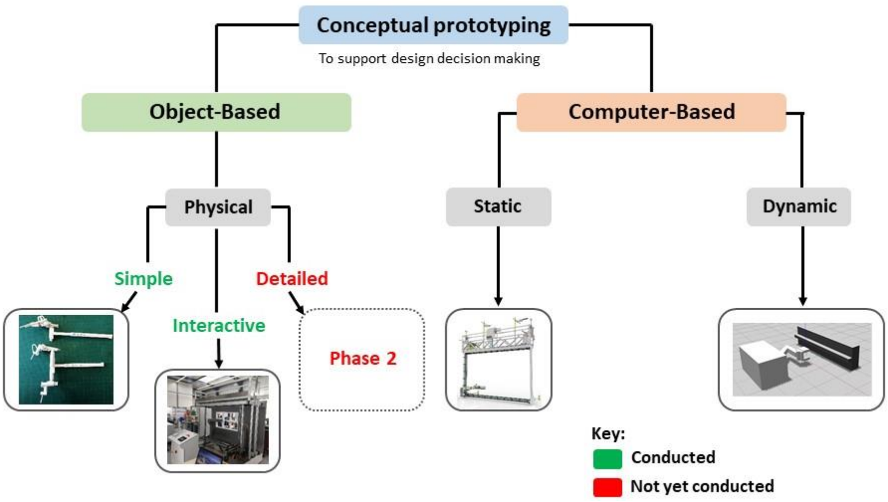


Figure 88: OCR prototyping sequences.

3.9.2 Prototyping sequence

Initially, the abstract design is drafted based on the input from the stakeholders and aforementioned analyses, which indicates the primary design will be a system that is hoisted in front of the case building and performs the façade painting task. To test the initial design decisions, the author has produced an abstract 3D visualization that demonstrates the dimension and proportion of the design. Based on this exercise, the abstract concept has been validated. In the following month, a variation of designs has been developed by using the static computer-based method. Figure 89 illustrates the design development evolution of the OCR. The advantages of the static computer-based method include the 3D model offers an unambiguous representation of the design concept and it is in digital format so that it can be easily distributed over the stakeholders. The 3D model is easy to alter based on the feedback, which provides quantitative results, and design imperfection can be easily identified. The challenges of the static computer-based method can be described as time-consuming during the front-end designing stage. Additionally, another limitation is the limited sensory input, which means the 3D model cannot simulate the real operational environment (Peavey, Zoss and Watkins, 2012).

A range of scaled physical models, including two full system models, two end-effector models, and a stabilization system model was created to improve the kinematic layout, test the hardware integration, and determine the optimal DOF for the robot, see Figure 90. The full system model consists of the mainframe structure, moveable components that offer movement along X, Y, Z-axis, and four rotational joints that offer yaw along X-axis, and pitch along Z-axis. The model is made of plastic profiles so that the movements are possible by passive force.

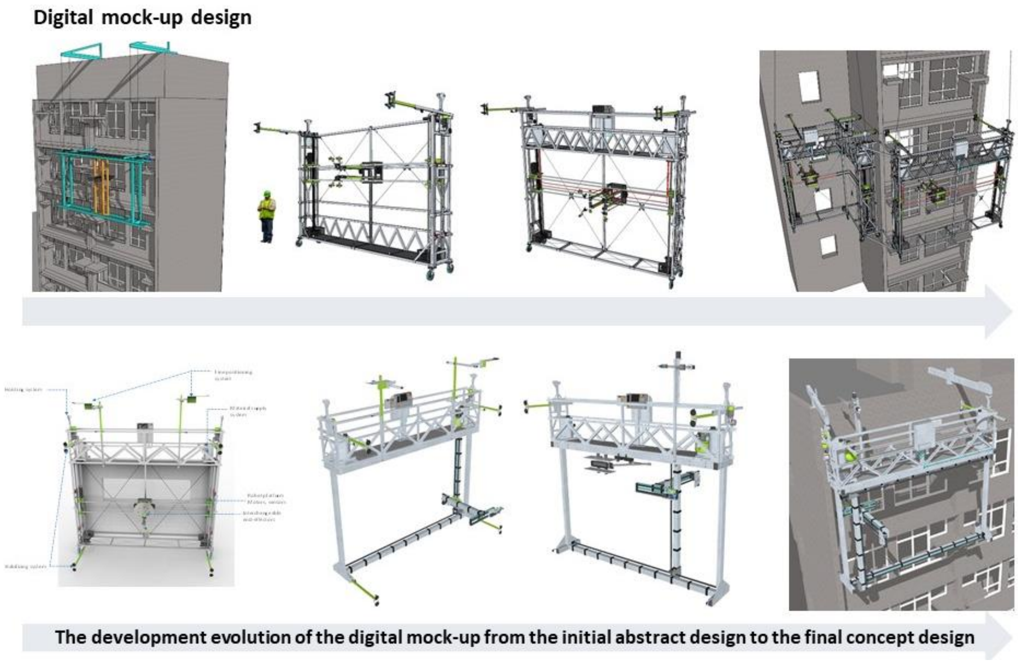
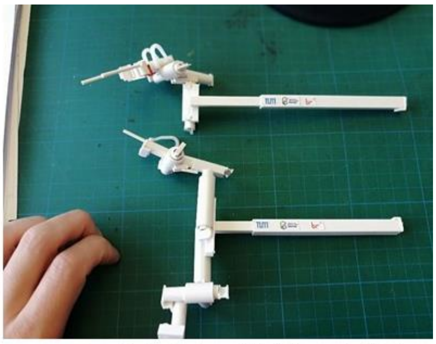


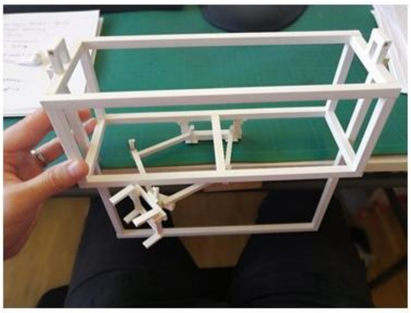
Figure 89: The development evolution of digital mock-up.

Due to the complex shape of the PCF, the composition of the linear actuator and the design of the end-effector must allow the paint nozzle to reach all corners of the façade. The design has been tested by using 3D model previously, yet it is necessary to explore the motion by using a physical model, which is the most straightforward way to identify if the design will function in the real physical world. For this reason, two end-effector physical models were made. The end-effector offers passive movement along Z-axis and yaw along X-axis, and pitch along Z-axis. This design demonstrates the essential movements that are required to achieve the design goal, and the simplified design has been used in the final design.

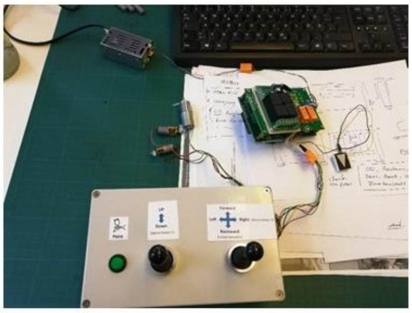
Small physical model of the system



Small physical model of the end-effector



Small physical model of the stabilization system



Simple robot joystick pendant

Figure 90: Examples of the scaled physical models.

The stabilization system development is supported by using a physical model to reflect the kinematic design of the system. The model is constructed with the same plastic profiles as used for the full system model, which consists of five rotational joints. The model can be manipulated by hands that have validated the design concept is technically viable.

To control the proposed OCR, two proposals were developed; one is to use an integrated control panel located in the suspended working platform. The second option is to use a handheld pendant controlled by the operator standing either on the suspended working platform or remotely. The author has consulted an experienced electronics engineer, who the father of the author. A simplified handheld joystick-controlled robot pendant was developed. It consists of a joystick pendant with two joysticks and one push button. It is connected with three mini step motors, which demonstrates the linear and rotational movements. The control principles were later introduced to the interactive robotic mock-up producer. Producing this robotic pendant is an extremely effective way in terms of enhancing communication between the designer and the technology integrators, and it speeds up the selection process of the appreciate control systems during the mock-up construction stage.

Based on the contract between TUM and the CIC, an interactive scale physical mock-up needs to be constructed mainly for demonstration and dissemination purposes. There are specific requirements in regards to the mock-up from the CIC, which include the mock-up should demonstrate the concept through the mechanical moment, it should be easy to assemble and disassemble in a confined space, and it should be easy to operate by a worker without previous robotic knowledge. Initially, it was advised by the CIC that a sub-contractor based in PRD region should build the mock-up due to a tight budget. However, the TUM team insists to collaborate with a local firm based in Germany. This decision has been made based on previous experiences when dealing with the international project especially when it involves prototyping. This measure is taken to ensure smooth communication, quality control, and intellectual property (IP) protection. It is vital to keep the suppliers and manufacturers within close proximity, especially in this case, because when there is any alteration in design or question from the sub-contractor, a rapid response is key to ensure accurate information transfer and communication can be made to avoid delays. Ultimately, the mock-up construction has been sub-contracted to HERO GmbH, a German company based in Sigmaringendorf.

First, the author designed an initial mock-up concept to determine the optimal scale for demonstration purposes and the buildability of the mock-up. After close collaboration between the designer, sub-contractor, and the CIC, the final scale is 1:3, which is a sizeable model with four DOF. The dimension of the mock-up is 2592mm in height, 1562mm in width, and 2400mm in length. The next step is to source the off-the-shelf product alongside the sub-contractor, to ensure the cost of the mock-up is within the budget. The final mock-up consists of eight key components including dummy suspended working platform, robot actuators, laser pointer, control unit, inverter, main structural frame, dummy wall, and protection skirting board. The dummy wall simulates the real operational environment, see Figure 91.

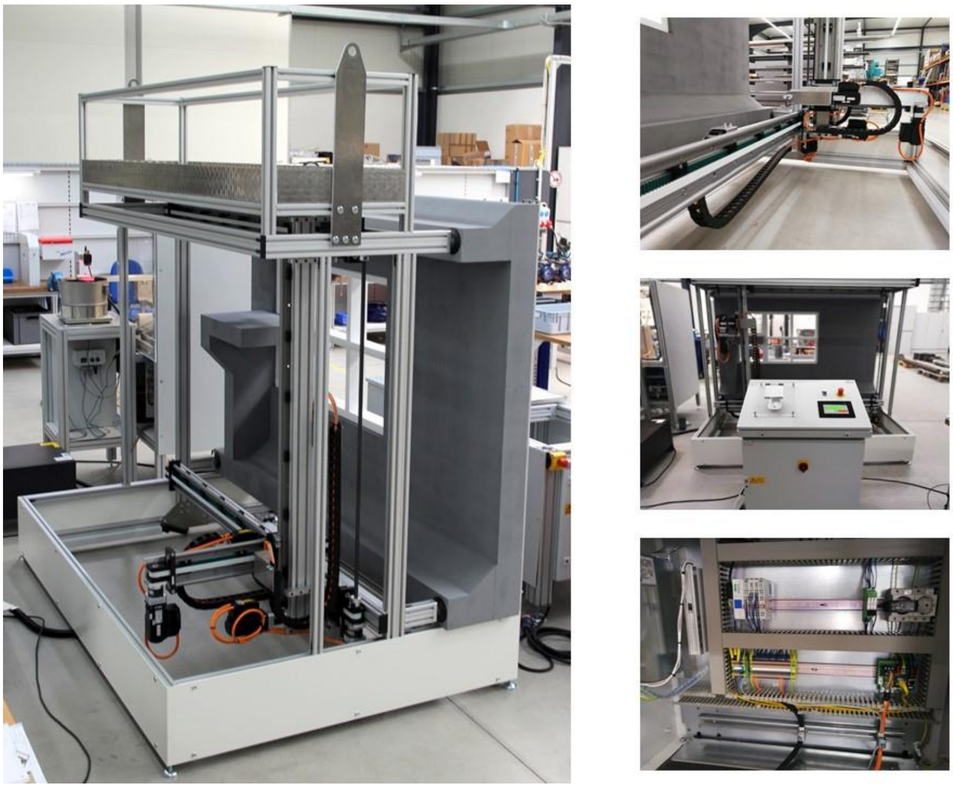


Figure 91: The 1:3 scale demonstration mock-up.

The reason to use a laser pointer instead of the operational spray nozzle is that the mock-up will be displayed in an indoor space, with Hong Kong's high humidity climate if the water is consistently sprayed on to the dummy wall, it may cause excessive mould growth, and ultimately affect the aesthetics of the exhibition, see Figure 92.

Figure 92: The details of the demonstration mock-up.

In addition, the author defined the travel path of the laser pointer based on the real situation, and with this data, the sub-contractor used an industry-standard PLC controller to pre-programs the mock-up. After the completion of the mock-up building, it was consecutively tested for seven days at HERO GmbH. Within the seven days, no malfunction was detected. The TUM design team travelled to HERO GmbH and received a one-day training program on how to assemble and dismantle the hardware and the electrics. A step-by-step user instruction manual was produced by engineers from HERO GmbH, which offers informative guidance for the training, see Figure 93. In the end, the mock-up is carefully disassembled into a few sections, then securely wrapped, packaged, and ready for the final shipment.

As mentioned earlier, the purpose of the mock-up is dissemination for the public and the industry awareness, to increase understanding of the proposed technology, and to stimulate the traditional construction industry for transformation. For this reason, the CIC and TUM team contacted CITAC to host the mock-up in the upcoming exhibition. For the past two years, CITAC acts as a knowledge hub that has promoted the state of the art innovative products, solutions, and applications from Hong Kong and international firms. With a strong commitment and reputation, the project team is confident that CITAC can provide a transparent and interactive platform to showcase the proposed OCR. The upcoming exhibition is divided into five thematic zones, which include Industrialisation, Intelligentisation, informatisation, Integration, and Infinity. The mock-up will be featured in the Intelligentisation zone.

The preparation tasks prior to shipping consist of communicating with CITAC exhibition organizers, planning delivery strategy, and on-site installation. During the preparation period, the following aspects were discussed and addressed. First, design the exhibition layout that could accommodate the mock-up with the proposed configuration. Second, contact relevant installation sub-contractors, for instance, make sure the locally certified electrician is available on the scheduled delivery date. Third, a safety operation manual and safety signage were prepared. Finally, a digital promotional presentation that demonstrates the proposed OCR and the CIC project is produced, which will be featured through an integrated tablets device.

The author and another TUM team member travelled to CITAC at the beginning of November 2018 to assist on-site installation and calibration. The installation took place from the 5th of November to the 7th of November, which includes system assembly, calibration, and training the CITAC staff, see Figure 94. Shortly after system installation, the team experienced an unexpected electrical issue. The team diagnosed the issue and identified the existing Residual Current operated Circuit-Breaker (RCCB) has been causing the issues, which is not powerful enough for the mock-up. The existing RCCB is 30mA that is designed for residential use; the issue was resolved by exchanging the existing RCCB to a larger 300mA industrial application RCCB. Moreover, the installation was successful thanks to CITAC's collaboration.

The author visited the exhibition in March 2019 and interviewed the general manager at CITAC. The manager claimed that the focus for the exhibition is to attract practitioners from the construction industry. Since the installation, the exhibition has hosted more than 3000 visitors from various industries. Positive and encouraging comments have been received from the visitors. All in all, the mock-up along with the interactive media has increased public awareness, understanding, and served as a very effective dissemination tool that reveals the potential of implementing automation and robotic technologies into the construction industry.

Training set up the mock-up following the installation manual **Safety operation manual** **Safety signage**

Figure 93: Safety operation manual, safety signage, and installation training.

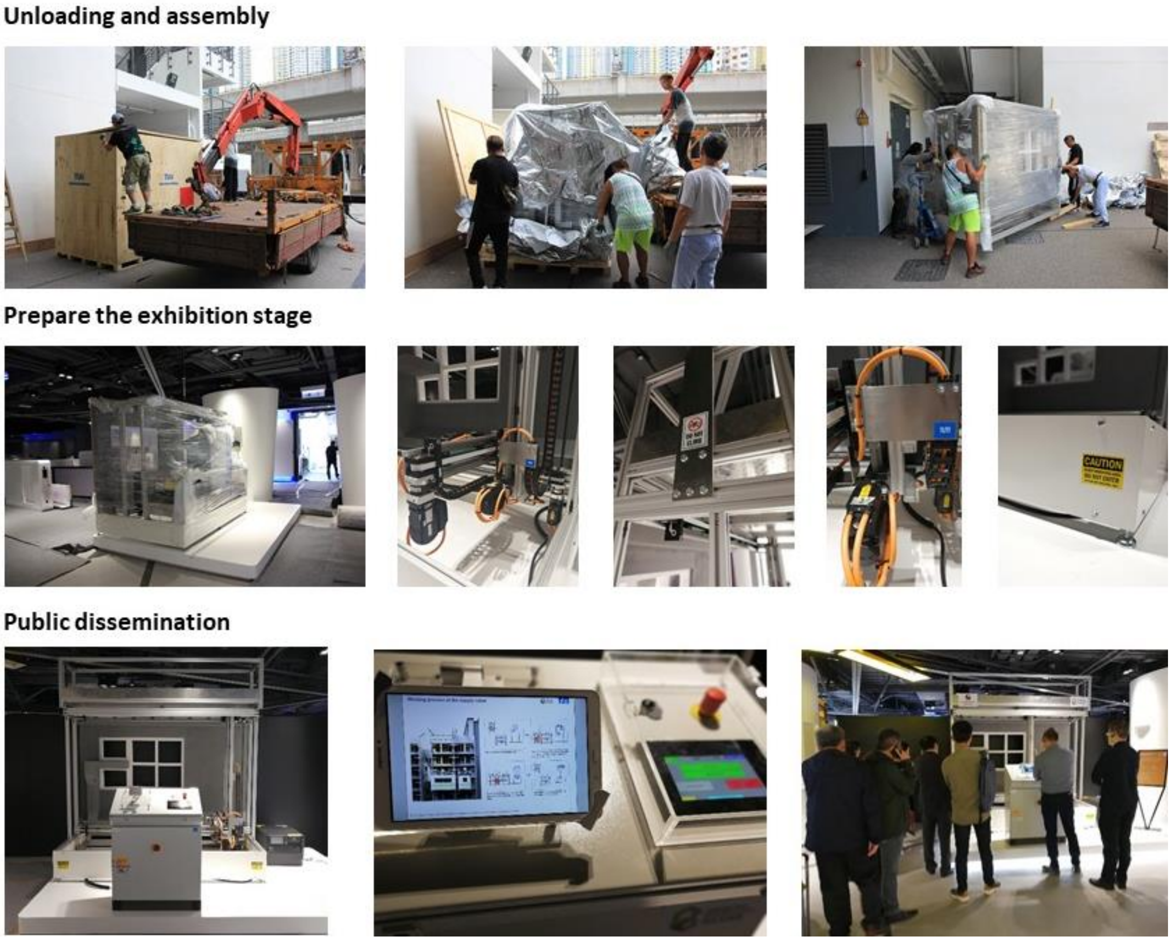


Figure 94: CITAC installation, calibration, and training.

3.10 Summary

In this chapter, based on the tasks that have been carried out in the first phase of the CIC project, a detailed description of each task is presented. Seven activities are described, namely Stakeholder analysis and initial requirement identification, on-line survey, on-site visit, Co-creation workshop, Initial system design, System development process, and iteration planning, and Conceptual prototyping and Initial dissemination.

The stakeholder analysis and initial requirement identification focus on presenting a method that is suitable for the application field, which is the implementation of OCR. In this case, the author first identified various levels of stakeholders based on their individual domain in order to evaluate their interests, demand, and influences to the proposed technology as well as the construction industry. Then, it was necessary to categorize the identified stakeholders into a hierarchical order, based on the hierarchical structure and with the understanding of the interests, demand, impact, product development driver, and hieratical order of the stakeholders. The author conducted initial requirement identification that further narrowed down the research scope and verified the initial functional, non-functional requirements, and potential conflict of interests.

Comprehensive data collection methods were presented, which are divided into three steps. First, an online survey was conducted that collected substernal online feedback from the involved participants. It also serves as a revelation that introduces the proposed technology to the construction industry. The second step is to have an on-site visit to identify what issues the front line works are facing and if the issues can be resolved by implementing automation and robotics technologies. By conducting an on-site visit, a range of tasks was identified that have the potential to be automated, for example, façade work, interior painting, and interior plastering. The aforementioned tasks are less dependent than other crucial structural works. On the other hand, the traditional construction industry imposes constraints that may cause a negative influence on adopting OCR. The third step is to have a co-creation workshop, wherein the outcomes become the principle guidance that supports the project aims to narrow down the priority areas and to map out strategies for implementing construction robotics or advanced automation systems in Hong Kong. The co-creation work determines the priority research area, which is to develop the multifunctional façade finishing robot as a demonstrator.

In the initial system design stage, the author introduced an approached that was adopted by other industries. The approach can be divided into two functions, one is called the allocation of function, which is used to identify which task should be automated or remain manual. The second function is called type and level of automation, which assists the designer in deciding which type of automation and what optimal levels of automation need to be applied to the robot. In addition, the design process was described, and the reason for making each design decision has been illustrated in detail.

During the system development process and iteration planning stage, APD approach has been considered to be the appropriate PDP for OCR as opposed to the waterfall method and the spiral method. The incremental method assists the designer in satisfying all requirements of the client while planning, deciding a realistic target, and dedicating the right amount of resources to achieve the design goal.

Evidently, based on the contribution form this chapter, implementing OCR in the traditional Hong Kong PHC industry is viable; the comments from the industry practitioners are positive. However, this is an incremental implementation procedure, which requires support, devotion from the construction industry, yet more importantly, interdisciplinary collaboration from other related sectors. The next chapter discusses the business strategy of how to promote the proposed OCR as a commercial product. Furthermore, the incremental implementation methodology that is featured in this chapter lays a foundation for later formulating the industry guideline.

4 Business strategy development

The previous chapter presented a detailed methodological approach of how to conduct various key tasks during the first phase of the CIC project. The objective of this chapter is to identify target markets and key customers and then evaluate the barriers and drivers that have implications on potential market uptake and business strategy development of the proposed OCR through the identification and explanation of the market analysis, market positioning identification, customer segmentation, and value proposition. A CBA based on the accumulated data will help guide the structuring of an applicable business model.

For this research, the author assumes that the proposed OCR will be launched and implemented in Hong Kong in the near future. With this assumption, the author will analyse the business strategy that is most suitable for the proposed system as well as explores the marketing strategy for the proposed OCR and how to translate the strategies into action through various methods. Specifically, the author would like to explore the potential business opportunities that Hong Kong has to offer, especially in terms of the government support for innovation and technology (I&T) in high-tech business.

4.1 Local supports and initiatives

Hong Kong offers an excellent geographical location, which is well-connected to mainland China, and the rest of the world. The Hong Kong economy enjoys minimal government interference and is one of the most transparent economies in the world. Hong Kong benefits from free ports, a system of low taxation, and a corruption-free government that is able to draw global investments (HKMPD, 2019). Supported by modern infrastructure and an international lifestyle, many international companies and highly skilled persons have settled down in Hong Kong each year. In addition, the close proximity and special relationship between Hong Kong and PRD municipalities will be reinforced by the Great Bay development plan. This development initiative presents an exceptional opportunity for Hong Kong to embrace traditional industries like financial services, professional services, logistics, and international marketing and trade while at the same time expand to new components in the field of high-tech industries, such as Artificial Intelligence (AI), Big Data, and advanced health care service (Fung, 2019). Noting these advantages, it is clear that Hong Kong presents a strategic location with support for innovative businesses, like OCR ventures, to flourish.

Innovation and technology are two key factors for continuing economic growth and have been treated as a high priority by the HKSAR. One of the objectives of the research is to explore applicable methods that will bring OCR from the conceptual stage to commercialization. Therefore, besides relying on business planning, it is essential to understand the incentives and initiatives available locally. To promote home-grown knowledge-based business sectors, the Innovation and Technology Bureau (ITB) was established in 2015 with ambitions of embracing applied research and development, encouraging entrepreneurship in regard to highly innovative products, developing incentivizing measures and policies in conjunction with the government body, and facilitating high-tech business ventures in Hong Kong and beyond. As a subdivision of the ITB, the Innovation and Technology Commission (ITC) provides a number of funding schemes that support I&T development in Hong Kong known altogether as the Innovation and Technology Fund (ITF). The schemes under ITF are divided into five focus categories based on supporting directions: Supporting R&D, Facilitating Technology Adoption, Nurturing Technology Talent, Supporting Technology start-ups and Promoting I&T Culture, shown in Figure 95.

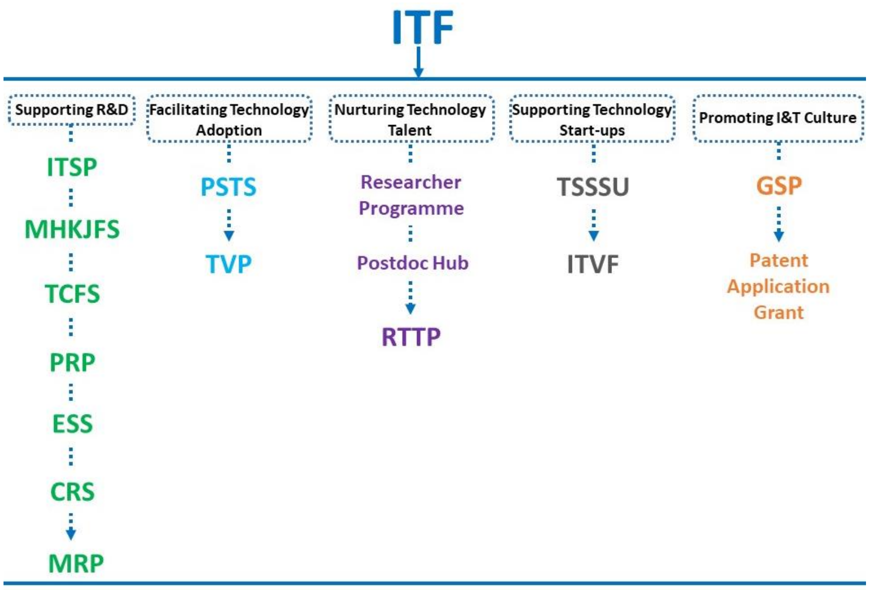


Figure 95: The innovation and technology fund structure.

The aforementioned schemes are relevant for launching OCR in Hong Kong, especially from the perspective of establishing local business enterprises for business operation and implementation. The ITC scheme information is public and is accessible through their official website. Each scheme has its own dedicated page with a clear guideline regarding eligibility, application submission, application forms, and other useful information. A brief introduction of the schemes is illustrated in Table 49.

Table 49: The I&T supporting schemes in Hong Kong, based on (ITF, 2019).

Schemes to support I&T in Hong Kong	
Title	**Description**
ITF	Launched in 1998, governed by the ITC, the ITF aims to encourage local companies engaging in innovation activities and is the main funding scheme that also covers most of the schemes featured in this table.
ESS	ESS is the major funding initiative under ITF that aims to encourage the private sector to invest in I&T-related research and commitments.
ARF	ARF is a venture capital fund to support R&D, commercialization of innovative products, and increasing competitiveness of local companies in high value-added markets.
ITSP	A scheme administered by ITC with the aim of encouraging local businesses to upgrade technology and introduce innovative ideas.

PRP	PRP aims to support research collaboration between local universities, research institutions, and private companies.
MRP	MRP encourages universities to carry out more midstream research and enhance international collaboration with other universities and research institutions.
CRS	CRS aims to encourage local companies to reinforce collaboration with appointed public research institutions. A significant amount of cash rebates are offered to those companies that engage in specific R&D projects.
ITVF	ITVF encourages local investment in I&T driven start-ups. “The Innovation and Technology Venture Fund Corporation” (ITVFC) coordinate this scheme.
TSSSU	The funding provides finance to six local universities to support academics to commercialize their R&D results.
Researcher Programme	The programme is formerly known as Internship Programme that supports university graduates to pursue their career in the I&T sector.
RTTP	This scheme aims to support individual skilled talent, as well as subsidise staff training in high-tech sectors.
MHKJFS	Launched in 2018, this scheme aims to encourage further R&D project collaboration between Hong Kong and Mainland China.
TCFS	This scheme aims to stimulate collaboration on R&D between Hong Kong and Guangdong province, Shenzhen.
Patent Application Grant	This grant aims to support local companies and individual talent to apply for intellectual property rights based on their own initiative.
PSTS	PSTS supports the production of prototypes, pilot runs, or innovative products that are not yet ready or available for market launch.
TVP	This program was launched in 2016 as a pilot trial that aims to subsidize efforts made by local SMEs in improving the existing productivity and technology transform.
Postdoctoral Hub	The scheme is part of the RTTP and aims to offer financial support for postdoctoral talent in ITF R&D projects
GSP	This programme aims to support non-R&D oriented projects that contribute to the areas of embracing I&T and transforming traditional industries.

With the support from these incentive schemes, Hong Kong offers an exciting opportunity for businesses, in particular for I&T oriented start-ups. Furthermore, Hong Kong offers a diverse platform and ecosystem that focuses on supporting I&T-oriented local and international entrepreneurs. The supporting platform is divided into three categories based upon business orientation: government development agencies that aim to guide and support companies as they develop; the incubators and business accelerators that facilitate corporate services, training, start-up services, networking, and investment opportunities; the early-stage investor associations that offer various ranges of venture capital and angel investment for business start-ups. Figure 96 shows some examples of how organizations are allocated to the corresponding category based on its business orientation.

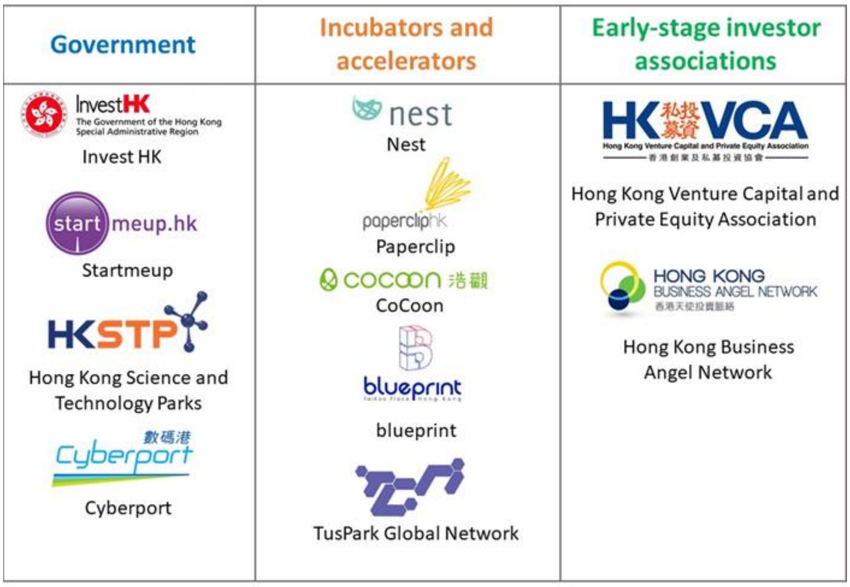


Figure 96: Entrepreneur community supporters, based on (KPMG, 2019).

The CIC is the leading force that drives research and innovation in the Hong Kong construction industry. As part of the organization's initiatives, the CIC has launched the CIC Research and Technology Development Fund (CIC R&D Fund) to support R&D efforts and I&T activities that cover Building Information Modelling (BIM), Construction Procurement, Construction Productivity, Construction Safety and Health, and Environment and Sustainability topics. The CIC R&D Fund is governed by the CIC and includes three schemes, each either their own focus: the Explorative Project Scheme (EPS) promotes research or products proposed by local research institutes that are still in the research phase and have not yet reached the market launch stage and together with the PSTS scheme, the combined funding schemes provide additional support for pilot studies and trial runs for research on the that all the IP generated through EPS and PSTS will be owned by the CIC; the Collaborative Project Scheme (CPS), which requires collaboration between local research institute and the local industry, focuses on the applicability of the research and aims to transfer research projects to practical applications under two types of IP ownerships b the project co-applicant – one where the co-applicant is responsible for covering at least 25% of the overall project funding but will give IP ownership and four years of exclusive rights to use the research result to the CIC and one where the co-applicant covers 50% of the funding and therefore owns the IP; and the KPI Improvement Project Scheme (KPIS), which focuses on health and safety, productivity, and sustainability and promotes practical adoption in the construction industry, but here the CIC is responsible for covering at least 70% of the research costs while the IP is owned by the applicant. These funding schemes offer great financial and institutional support for research institutions, start-ups, and local businesses. Prior to application submission, the interested party should evaluate the terms, the conditions of each scheme, and make sure it is appropriate for the business development strategy of their organization.

The Development Bureau of Hong Kong and the CIC is advocating R&D in the construction industry and aims to strengthen the industry's competitiveness while enhancing sustainable development. The CIC construction innovation award was launched in 2015 to further encourage I&T activities in the construction industry and to inspire young innovators to share their innovative concepts with the industry. The competition is held yearly by the CIC and consists of three awards including international awards, local awards, and young innovator prizes. The submitted projects go through a series of evaluations and are judged by industry experts. The main judging criteria are the benefits to the industry, originality, and applicability. Over the years, many innovative concepts were realized from entering the competition and have been transferred into practical application through a joint effort between the CIC and the industry.

It is widely believed that innovation is the key to success in the era of innovation. From HKSAR to the local institutions, there are significant resources that have been allocated to support the high-tech industry as well as to empower the Hong Kong construction industry to grow and prosper continuously. However, beyond financial and fiscal supports, a well thought business strategy is crucial to translating strategies into action as well as for ensuring that the final product will address the practical needs of the industry. In the next section, the author will demonstrate applicable methods of how to prepare an early-stage business strategy while the proposed OCR is still under development.

4.2 Market positioning

The proposed OCR is located in a distinctive market that relies on existing technology to open up new market opportunities either in markets where those technologies already exist or in new markets. The proposed OCR is, therefore, a type of niche creation. One of the most important qualities of any niche creation is to match the customer needs and to continue to satisfy their requirements through product iteration (Abernathy and Clark, 1985). One of the channels to understanding customer needs is through systematic stakeholder analysis as discussed in chapter 3. An alternative channel is through market positioning to evaluate a customer's perception of the product, competitive edge, and product attributes. In addition, positioning the new product in the target market segment and assessing its ability to adapt to diverse changes in the market demand is important. This section will identify the key activities for how to conduct market positing in the context of the proposed OCR.

What is market positioning? Why it is important? How could the proposed OCR be positioned in the marketplace? Market positioning has many definitions according to various researchers, but in the case of OCR, it is the allocated position of the product in both the existing and future market as well as how the product will be perceived by stakeholders against potential competitors (Chowdhury, 2013). The key outcome of a successful market positioning is to fully understand the target market and the attributes of the product and to then offer a customer-oriented value proposition that is fully aware of the competition in the marketplace (Cronshaw, Cubbin and Davis, 1990). It also identifies the uniqueness of the product and sets a general guideline for market penetration (Kotler and Keller, 2016). The proposed OCR can be positioned through four channels including positioning by competitor competencies, positioning by attributes, positioning by product users, and positioning by usage. The following exercise demonstrates the method used by the author to evaluate the appropriate market position for the proposed OCR.

As shown in Figure 97, the positioning by competitors competence matrix divides the potential competitors by their core business and competence. The four competencies are High-Tec, research, innovation, and manufacturing and are organized by the most relevant companies and institutions and then allocated into the corresponding category based on their competence. The major players in the construction equipment business have been placed in the manufacturing category, such as Hitachi and Caterpillar. The top-ranked international robotics companies, such as ABB, and Kuka, are in the High-Tec category. The research institutions and universities that have conducted construction robotics-related research, such as NTU, and ETH Zurich, are in the research category. Companies such as OKIBO and Robot at work that specialize in OCR R&D similar to the proposed OCR are in the innovation category. It is important to note that some companies overlap the competence boundary because some companies engage in cross-disciplinary research activities. For examples, the Volvo Group launched the Collaborative Robot Systems Laboratory (CRS-lab) and works closely with local universities, and the ETH Zurich collaborates with ABB developing wooden structure fabrication robot. The proposed OCR is positioned between the innovation and research categories because in the early stage, the product is being developed by the university, but later will be progressively commercialized through innovative start-ups.

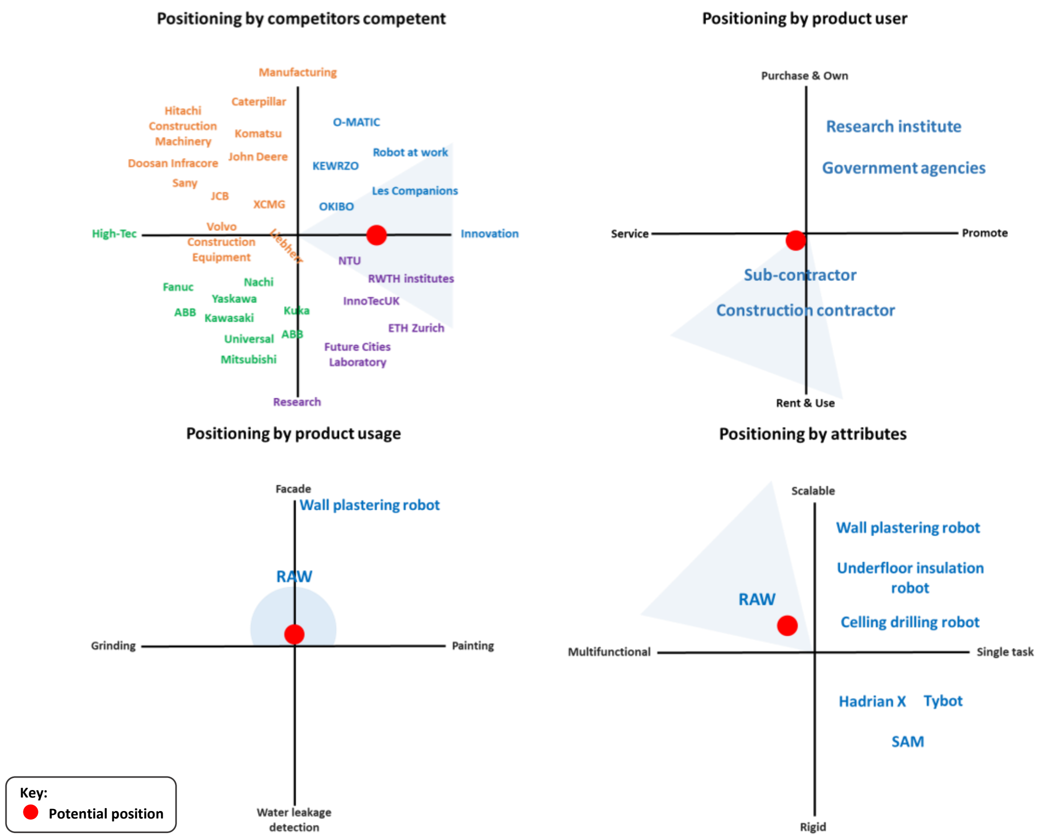


Figure 97: The positioning by competitors competence matrix divides the potential competitor by their core business and competence.

The positioning by product user matrix shows how the potential customers would use the product and is divided into four methods: promote, purchase and own, service, and rent and use.

The identified customers are research institutes, government agencies, sub-contractors, and construction contractors. Based on the feedback from the industry practitioners, the most economical and practical method for launching a product is through renting and through acting as a service provider.

The positioning by the product usage matrix is categorized by the potential product applications that have been identified previously. The applications include general façade application, painting, grinding, and water leakage detection. After extensive market research, two robots were identified: a wall plastering robot developed by OKIBO and RAW developed by Robot at work. The wall plastering robot is a single-task robot while RAW offers a flexible design that can be used for multiple building façade tasks. The proposed OCR will be positioned in a similar location as RAW, focusing on façade application and, in the early stages, specializing in façade painting tasks.

The positioning by attributes matrix is divided by characteristics of the product: if the product is scalable, if the product is rigid (meaning its function cannot be expanded), if the product is the single task or if it is multifunctional. Seven robots were selected and positioned into different categories based on their attributes. The proposed OCR will sit where RAW, which possess the ability to be scaled up and potentially used in multifunctional applications, is located.

The market positioning exercise provides a strategy that not only focuses on competitors but also looks into aspects of the customer, the product usage, and the product attributes. According to the analysis, the strategy assists in identifying competitors. Robot at Work, and their product RAW, is the primary competitor of the proposed OCR, due to their dominant position in the market and their focus on façade application, which is multifunctional, adaptable, and highly scalable. Other companies that deal with construction robotics are classified as secondary competitors while construction machinery suppliers and conventional robotic companies are tertiary competitors. The strategy also forecasts the prospective product position for the proposed OCR in comparison to its potential competitors. In addition, the strategy will have an implication on product finalization, marketing, pricing, production, distribution, life-cycle management, and iteration strategies. After gaining an understanding of the market position of the product, the next step is to understand how to satisfy the customers' needs by conducting customer segmentation analysis. Furthermore, by investigating the value proposition to understand how the proposed OCR will generate value to the target customers.

4.3 Customer segmentation and value proposition

The construction industry has been said to possess highly fragmented market segments, diverse value chain, and varying customer demands (Abadi, 2005). Customer segmentation assists the project team in dividing the diverse market and value chain into understandable attributes. It also divides the market into groups of customers based on their behaviours and characteristics. By segmenting customers, it will enhance the understanding of the existing or prospective customers, address market challenges and opportunities, narrow down target groups, and prepare effective channels to raise product awareness in the future. The first step is to carry out the consumer-oriented market segmentation to define the potential market. The second step is to analyse the characteristics of the customers. The third step is to identify the needs or gains of customers within the potential market. The final step is to evaluate the pains or constrains of the defined customers (Dibb and Simkin, 1991).

In general, there are four categories within the potential market including the available market, the qualified available market, the target market, and the penetrated market. The available market is one in which potential customers are willing to and have sufficient resources to access the specific market or service. The qualified available market is those customers in the available market who are legally permitted to buy or use the product and services. The target market is the customers that should be the focus of the business and service. The penetrated market are those customers who already use the product or service. In the case of the CIC project, because the product is still being developed, the penetrated market will not be considered.

Building construction contractors, construction machinery industries, existing robotic and automation industries, the CIC, and government authorities are in the potential market category. Even though the CIC and the government authorities are not directly associated with the daily business aspects of the product, they have a significant impact on the success or failure of the business. For example, the proposed OCR has the potential to receive incentives from new government policy or regulations and the product could gain public awareness and greater confidence from the construction industry if it is promoted through the CIC. The available market consists of general building contractors, construction machinery rental or retail companies, and specialized building providers. General building contractors and construction machinery rental or retail companies are the qualified available market while construction machinery rental or retail companies are the target market Table 50.

Table 50: The market segmentation.

Market analysis	
Potential market	• Building construction contractors • Construction machinery industry • The existing robotics, automation industry • The CIC, the government authorities
Available market	• General building contractors • Construction machinery rental or retail companies • Specialized building service providers
Qualified available market	• General building contractors • Construction machinery rental or retail companies
Target market	• Construction machinery rental or retail companies

As part of the customer segmentation process, one step was to identify the characteristics of the customers in the potential market by investigating the operational activities of the potential customers and determining the criteria of their intentions and objectives related to their businesses (demonstrated as customer tasks in the customer segments canvas, see Figure 98. The identified criteria helped define the gains and pains of the customer if the proposed technology were implemented. The building construction contractors' main tasks are to deliver construction work of a higher quality on time, on budget, and safely. The core tasks of the existing construction machinery industry include researching, designing, manufacturing, and selling construction-related machinery. Similar to the existing construction machinery industry, the existing robotics and automation industries' main tasks are dealing with R&D, production, and marketing robotic products. The CIC and the government authorities are interested in stimulating the conventional construction industry by encouraging the industry to adopt innovative technologies.

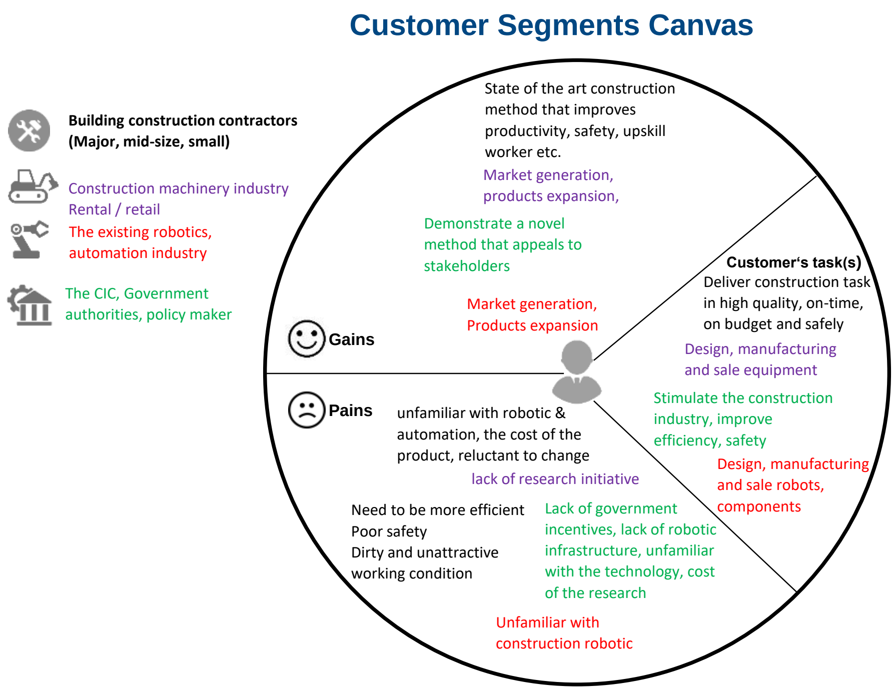


Figure 98: The customer segments canvas.

By implementing the proposed technology, the primary gain for the building construction contractors includes attaining an innovative method that could potentially increase productivity, safety, and labour skill. In other words, these gains are very similar to the central benefits that attract the industry to adopt any new technology. The main attraction to the existing construction machinery industry and the existing robotics and automation industry is new market generation as well as product expansion. The CIC and the government authorities are interested in conveying the industry's demands through communication and research in order to disseminate exploitable outcomes. On the other hand, the pains or constrains for building construction contractors wanting to adopt the proposed technology include unfamiliarity with the technology, the costs, and their inability or unwillingness to change conventional working methods. It is understandable given that the conventional working methods are supported by a well-established supply chain and administered by regulations that would make it very challenging to accept rapid changes. It would, therefore, be important that the procedure goes through an incremental, step-by-step process of change. The biggest challenge for the existing construction machinery and robotics companies is that they are not aware of the market gap and are unfamiliar with construction robotics and would, therefore, find it difficult to detect the potential market. The challenges for the CIC and the government authorities are unfamiliarity with the technology, a lack of incentives, a lack of financial support for such innovation, and thus a lack of research initiative, and an existing infrastructure that is not adequate for implementing the proposed product instantly.

After segmenting the customers based on their characteristics and understanding their gains and pains, the next step is to evaluate how the product will bring value for a target customer group using a method called a value proposition. This practice is one of the key marketing research strategies and is used to evaluate the principle value that the product offers to the target customer in order to deliver a product that matches what the customer wanted with the given resources, which is the key to successful market launch (Kotler *et al.*, 2005). Different stakeholders will have various perspectives concerning values and it is important to be aware of the different types of values, whether that means direct financial gain, institutional benefits, or satisfaction in service. A value proposition based on customer insights is used to formulate values that are useful for the development team to match expectations between corporate and the customer (Osterwalder *et al.*, 2014). In addition, a value proposition unusually penetrates through the entire life cycle of a product, from the creation stage all the way to the iteration stage (Hassan, 2012). This dissertation concentrates on the value creation stage due to the proposed OCR still being under development.

The value proposition canvas, as seen in Figure 99, features the key customer segments to the right and the unique selling proposition to the left. The unique selling proposition is divided into three parts including product and services, gain creators, and pain relievers. The gain creator formulates the factors that represent the principal selling points of the proposed OCR and justifies how the gains in the customer segments are dealt with. The pain reliever provides solutions that the product and the development team could offer to address the identified pains in the customer segments canvas. The listed features in both the gain creator and pain reliever can also be used as the intended design objectives of the proposed product. Finally, the product and services portion showcases the uniqueness of the proposed product in comparison to a competitor's product as well as the available services, a summary of this is shown in Table 51.

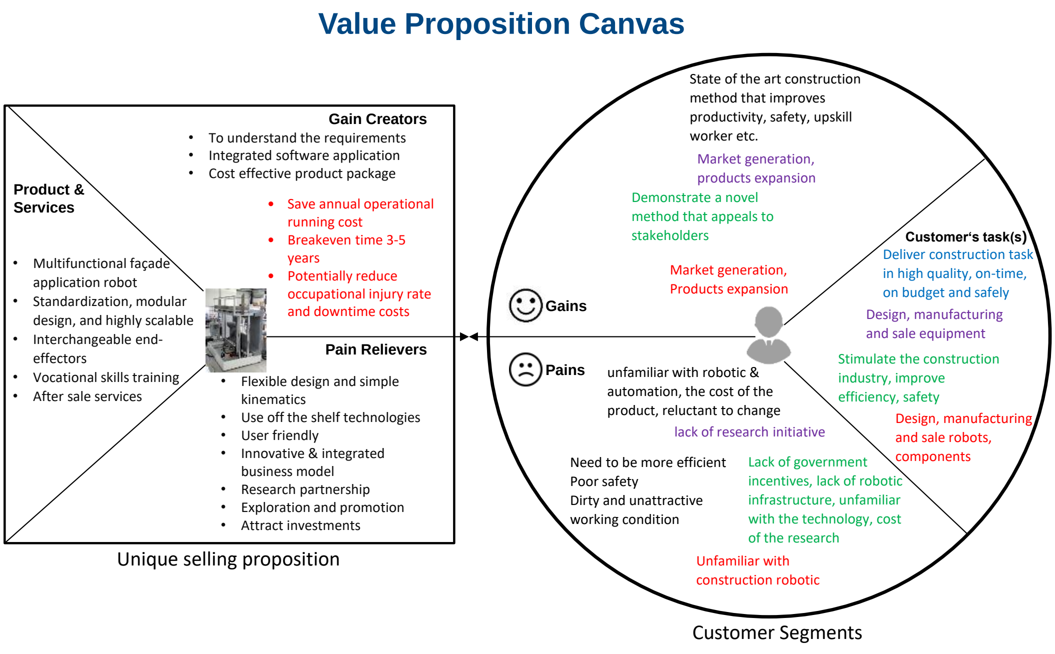


Figure 99: Value proposition canvas.

Table 51: The product and services portion.

Gain creators	• To understand the requirements • Cost-effective product package • Integrated software system (control, data transfer, sensory, etc.) • To save annual operational running cost • To reduce the breakeven time (payback time) • To reduce occupational injury or fatal accident
Pain relievers	• Flexible design with simple kinematics • Durable and reliable • Use off the shelf technology • User-friendly • Innovative and integrated business model • Research partnership • To attract investment
Product and services	• Multifunctional façade application robot • Standardization, modular design, and highly scalable • Interchangeable end-effectors • Accessories • Sale and system leasing • Vocational skills training • After-sale services, system upgrades • Technical consultation

To transfer an OCR product from the conceptual idea to a marketable version requires a systematic approach. It is important to consider a customer's perception of the product value from an early stage so customers and key stakeholders are welcome to participate in the value creation stage. Gaining comprehensive insights into the product value proposition will enhance decision-making and validate the product development direction. Because additional investments are needed to move the project forward, the identified product values can be used for convincing prospective investors on why they should invest. Unfortunately, the predicted value from an early creation stage is not sufficient for a potential investor to decide whether to allocate resources toward the proposed OCR. For this reason, a comprehensive CBA study was requested by the CIC as discussed in the next section.

4.4 Cost-benefit analysis

At the end of phase one of the project, the proposed multifunctional façade finishing robot had demonstrated its applicability through design and its added-value through the initial value proposition. Next, it was critical to secure additional funding so that the project could smoothly entre into the second phase and even though the second phase of the project does not fit into the scope of the dissertation, it is relevant to document how to conduct CBA in the context of the project. CBA and CEA are useful tools for measuring and evaluating the investment potential of a product and can also be used as a guide for investors when making decisions on how to allocate research funding for a prospective project (Svensson and Hultkrantz, 2017). While CBA focuses on monetary costs and benefits, CEA focuses on non-monetary outcomes, such as incremental cost per unit of the effectiveness of intervention A versus intervention B.

Depending on what is being measured, the costs and benefits will fluctuate over the entire project life cycle (Svensson and Hultkrantz, 2017).

The monetary benefits of using robotic applications are easily quantified when the data relating to the costs, specifications, and performance of the robot is available. However, because the proposed OCR has not been finalized or field-tested, the cost of the robot can only be estimated using off-the-shelf products as a reference. The consumer value and other added values of implementing the proposed robot can only be estimated through initial value proposition and evaluated through rational assumptions with the help of previous experiences gained under similar circumstances (Warszawski, 1985). Even though there are many non-quantitative terms to be defined later in the project, it is more common for a potential investor to require a CBA during the early stages of the project, especially when an investor is not familiar with the future product. Fortunately, the data collected from previous investigations, such as the stakeholder analyses, the on-site case studies, the co-creation workshops, the initial designs, the dissemination, and the market positioning inquiries, provide valuable information for carrying out the CEA, which will provide insight on the overall incremental cost and benefit impacts of the proposed OCR. The data will then be used in conjunction with the CBA calculation. The CEA is divided into two categories: incremental costs and incremental benefits.

The incremental costs are R&D costs, investment costs, operational costs, infrastructure costs, set-up costs, maintenance costs, and indirect costs. Figure 100 shows the estimated behaviour of how the incremental costs will change in the various project stages. A detailed description of the individual incremental costs are:

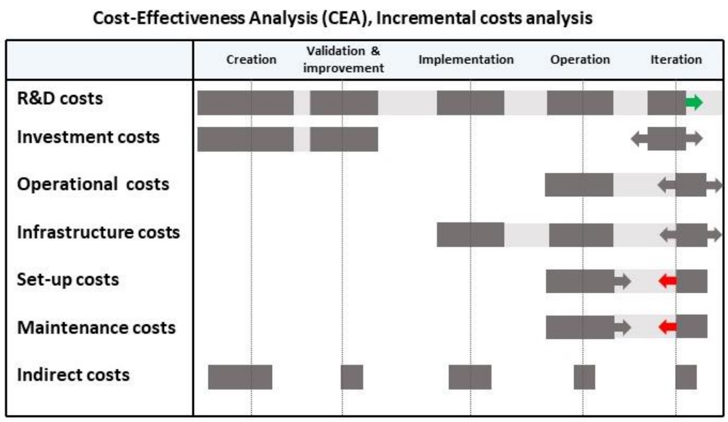


Figure 100: Incremental costs analysis.

- R&D cost: This cost includes labour, materials, facilities, travelling, and any other activities associated with researching, designing, testing, and launching the proposed OCR.
- Investment cost: This includes the initial investment, depreciation, and discount cost (Lewis, 2013). There are government policies that focus on the stimulation of growth and innovation by increasing investments to promote I&T activities (Aghion and Howitt, 2006). This cost also includes investments from private sources.

- Operational costs: This cost includes the resources that are consumed during robot operation, such as electricity, labour, material, and logistics.
- Infrastructure costs: This consists of site preparation, training, preparing assistive systems or accessories that will support the system operation and it can include hardware, structural alteration, software integration, and institutional efforts.
- Set-up costs: The costs include installation, logistics, testing, calibration, and programming.
- Maintenance cost: This cost includes repairs, inspections, and parts replacement.
- Indirect cost: This accounts for any other costs that have been generated by robot deployment.

As shown in Figure 100, the R&D costs continue throughout the project in order to maintain a long-term competitive advantage of the product (Rosenbloom, R.S., 1974). During the course of development, the investment costs will continue throughout the project, and although the investment costs will pause during the implementation and operation phases, they will resume in the iteration phase. The fluctuation of the operational costs will depend on the status of TRL, IRL, and SRL. The operation costs will taper off when the product is mature but consumables might add some operational costs during the iteration phase. The infrastructure costs will continue until all essential items are in place but when the IRL, MRL, and Market- Readiness-Level (MRL2) costs start, infrastructure spending will taper (Abernathy and Clark, 1985). The set-up costs and maintenance costs will only begin in the operation phase, once the system and market have matured, but will often cease in the iteration phase (Warszawski, 1985). The indirect costs are randomly distributed and due to a lack of data, it is difficult to formulate an exact pattern that indicates the exact timing of the indirect costs. Once the product and the market are mature, it will be possible to generate approximate costs based on the previous experience. Overall, the only costs that will conclusively continue throughout are those of R&D but these are highly beneficial to the development of the product.

As shown in Figure 101, most of the incremental benefits will progressively increase over the project duration. Although the identified incremental benefits are difficult to measure in monetary terms, they cannot be neglected. The incremental benefits are:

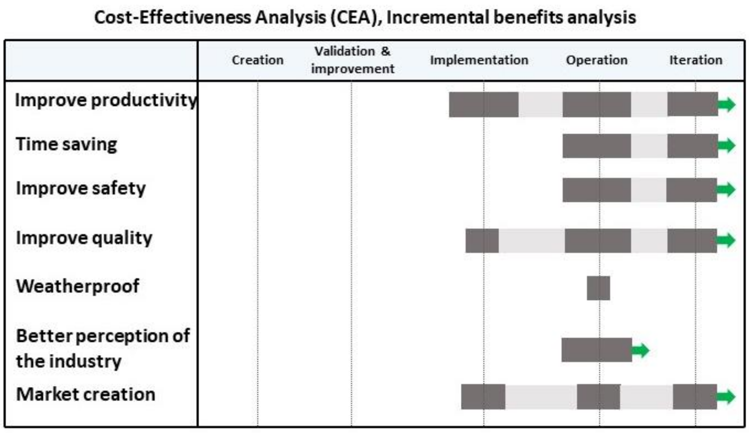


Figure 101: Incremental benefits analysis.

- Improved productivity: The proposed OCR will lead to a reduction or augmentation of human involvement thereby improving overall productivity.
- Time-saving: The system will reduce the overall time spent on dedicated tasks and will help mitigate the potential time spent on overtime or repeat work. (Hanna, Taylor and Sullivan, 2005) and (Thomas, 1992) have both found that repeat work has a negative impact on productivity and accidents rates.
- Improved safety: The system can help save lives and reduce work-related injury as well as reduce costs for accident-related compensation and mitigate the loss of productivity, delays, and damage of equipment (Everett and Frank, 1996).
- Improved quality: The proposed OCR will improve work quality in order to avoid rework or rejection due to poor quality.
- Weatherproof: The proposed OCR can perform under harsh weather conditions to avoid potential weather-related hazards.
- Better perception of the industry: Improvement of the conventional image of the construction sector to make it more appealing to younger generations (Warszawski, 1985).
- Market creation: In industries experiencing rapid technological change, a single company rarely has a full range of expertise needed to offer timely and cost-effective new product innovations (Teece, 2008). The OCR's position in a niche market presents opportunities to create new markets or entre pre-existing markets.

Because the proposed OCR is not yet developed, it is hard to accurately measure a CBA. For this project, the estimated manufacturing cost of the OCR was guided by the mock-up break down cost provided by HERO GmbH. Hip Hing Construction Co., Ltd. collects data regarding existing labour costs, operational costs, and estimated potential system transfer costs. Hong Kong Polytechnic University (PolyU) is, therefore, working closely with TUM and Hip Hing Construction Co., Ltd. to categorize costs and benefits and to provide quantifiable CBA results. A value-based price method, suggested by Abraham Warszawski, was adopted to estimate the Net Present Value costs and benefits (NPV) of a system (Warszawski, 1985). Using this method, the author assumes the operational speed of paint coverage of the proposed OCR is identical to a human worker. Moreover, the system is only upskilling one labour in this scenario due to the system still being under development and a lack of accurate operational data. The NPV can be calculated based on the following equation, see also

Table 52:

Net Present Value costs/benefits (NPV)= PV(B)-PV(C)

PV(B): b*Benefits (L)

PV(C): b*Costs (M1+M2+O+T1+T2)

$$b = \frac{(1+i)n - 1}{i(1+i)n} \text{(Discount rate)}$$

$$\text{(NPV)} = L\frac{(1+i)n - 1}{i(1+i)n} - (M1+M2+O+T1+T2)\frac{(1+i)n - 1}{i(1+i)n}$$

Table 52: The keys of the NPV equation.

Running costs	
Estimated Manufacturing cost of Robot	M1
Cost of robot maintenance per year	M2
Cost of robot operation per year	O
Cost pf robot transfer per year	T1
Training of staff	T2
Running benefits	
Labour saving (Upskilled labour)	L

Based on the equation above, the incremental impacts and NPV of the proposed façade finishing robot were evaluated. Only an initial estimation of the CBA was conducted based on the information at hand, but what is most noticeable is that the figures that impose a direct impact on payback time fluctuation are the manufacturing cost of the system and the number of labourers saved. Nevertheless, the CBA reflects an optimistic outcome, which is encouraging for the continued development of the proposed system into a fully functional prototype. Based on the data at hand, the estimated payback time is between three and five years, but in the next project phase, lab tests, calibration, and a pilot project will work to provide tangible information that can be used to support these initial CBA results. As mentioned earlier, implementing the proposed OCR should be an incremental process despite knowing that some of the direct benefits, value, and advantages might not be visible during the early development stage. Following full maturation of the product, the benefits will eventually penetrate all technical, social, and political aspects (Linner *et al.*, 2020).

The committee on productivity meeting was held on 26th March 2019 in the CIC headquarters where the author, TUM colleague, and Prof. Geoffrey Shen from PolyU presented the most recent phase two proposal and financial requirements to the committee board. The CBA results were an important part of the presentation as they allowed negotiations on the terms of the project. The committee board members were generally content about the technical aspects of the proposal, but they were concerned about the fact that the entirety of the R&D costs would be solely covered by the CIC. The committee board members did take into consideration that the CIC helped complete the task of developing an OCR mock-up that was tailor-made for the Hong Kong PHC industry. The mock-up itself was as a great asset for stimulating the industry for future development. The committee board members made a recommendation that TUM and PolyU should engage local construction industries to co-invest in the project and to then submit a CPS application with interested industry partners. As a result, the CIC put the phase two proposal on hold and will reopen it once an available industry partner is willing to share in the funding of the project.

Even though the project has been put on hold, their decision reflects how both investors and the construction industry feel about implementing the proposed OCR. First, the overall feedback has been positive, but the CIC has been trying to encourage industry stakeholders to be more involved in the development, to share in resource commitment, and to increase public awareness. Second, even though the CIC is aware of the positive expected market positioning of the proposed product, the conventional construction industry lacks the infrastructure that could facilitate the technology. For instance, after-sale services, maintenance, certification, and training will take time and money to be established. There are still unforeseen risks in addition to the huge investment, which is why the CIC suggested splitting the costs in order to share the uncertainties with co-investors. One practical solution is to form an entity, whether that be a spin-off company or joint venture organization, to continue with phase two of the project. The company will be dedicated to OCR oriented services, but this would require an adequate business plan, government incentives, and systematic coordination. Because the proposed OCR belongs in a niche market and most of the product is either under development or newly launched, there are very few business models that can be used as a reference. The following section will discuss the best business strategies to pursue based on interviews with industry stakeholders and potential competitors and will investigate what types of a business plan will be applicable for the proposed OCR if the product is commercialized in the future.

4.5 Potential business plan

The following section elaborates the potential commercial exploitation and market uptake of the proposed OCR. First, the target market and market value are identified. Second, market awareness based on interviews between the industry practitioners and potential competitors is evaluated. Third, the elements that drive and hinder the proposed technology are evaluated. Fourth, business opportunities are proposed, risks are predicted, a feasible solution to overcome the identified challenges is recommended, and the gap between I&T and the market uptake is bridged. Since the proposed OCR has not yet reached the stage where it is ready for full-scale commercial implementation, the proposed business strategy assumes there exists an entity to further develop the concept to commercialization level.

4.5.1 The target market

The proposed OCR focuses on the Hong Kong PHC sector and the first-generation product was specially developed to deal with façade painting applications. As mentioned in chapter 2, the government aims to construct more than 480,000 units of public housing in the next decade making the projected market size large. Because the proposed OCR was developed to address a painting task, according to the results from the customer segmentation conducted earlier, the target market can be categorized into four sectors. First, the general contractors that specialize in façade painting tasks. Second, the machinery suppliers that provide equipment and tools for façade painting applications; for example, airless spray and painting nuzzle suppliers. Because the proposed OCR is an upgrade for existing systems, it has an advantage in that it can tackle conventional equipment suppliers who have already penetrated the market and gained a stable customer network. Third, the existing robotic companies, especially those S&MEs who find the competition in the existing industrial robotic sector too competitive, are probably willing to search for an alternative market within the robotic domain. Fourth, the government training bodies who offer training programs for construction machinery operators.

The proposed OCR does belong to a niche market and because of this, most of the systems with similar functions are either still under development or are only in the pilot testing stage. These similar systems neither pose an immediate threat nor are they commercially comparable. It is therefore important to be aware of what the target market feels about the proposed technology. The next section will describe the market awareness from the perspective of the Hong Kong construction practitioners and potential foreign competitors.

4.5.2 Market awareness

The proposed technology is relatively new to the construction industry and, as expected, there are some misconceptions about it. Typically, when the word robot is used, people often imagine the robot as being either humanoid or similar to a conventional industrial robot. Given this misconception, the author conducted several group interviews with construction practitioners in Hong Kong as well as construction robotics firms in Denmark and Norway to understand their preconceived notions and ideas about robots. For a confidential reason, the interviewee’s organization and name will not be mentioned here.

Most of the interviewees were Chief Executive Officers (CEOs) of local construction companies; overall, they do believe that automation and robotics can improve construction productivity and safety. One of the CEOs from a major public housing construction company suggested that the OCR needs to first assist human labour with the highly repetitive manual tasks and then to develop into an application that can totally replace human labour for highly hazardous jobs. Another CEO from a local contractor mentioned that replacing human labour on the construction site is extremely difficult so researchers need to figure out how to leverage people and how to use OCR to complement human labour instead of replacing them. A CEO of a local construction company was concerned about the feasibility of OCR mentioning that implementing robots on-site could be very costly in addition to the lack of supportive infrastructure that would make it even more expensive. He went on to mention that the low-profit margin from the construction works to adopt OCR might be a distant dream, but he also made some recommendations, such as maximizing the usage of the system to avoid redundancy or renting as a more attractive option for the industry. Finally, one of the managers from a construction company expressed his concerns regarding the additional safety hazards of using robots on-site for human labourers. Even though the utilization of robots can potentially save lives by doing dangerous jobs instead of humans, when humans work with robots in close proximity, it could impose risks for human labourers. This risk assumption was based on knowledge from the manufacturing sector, where robots are often separated from human labour by a protection cage. Unfortunately, on a construction site, it is impractical to install safety cages or to even keep the robot stationary for the designed purpose. Therefore, because the robot is mobile and working alongside human labourers, a certain degree of unforeseen risks are at play. For the OCR to be applied safely, he recommended that a safety regulation specifically drafted for OCR safety operation to govern health and safety issues would need to be implemented. While these concerns do need to be addressed, other interviewees expressed more optimistic views.

A senior management member of one government body holds the view that even though the initial cost of the robots is high, labour costs continue to rise thereby allowing the robot to save costs through improving construction efficiency. In addition to cutting labour costs, the cost of the component and robotic parts will decrease once the market achieves a certain economy of scale. Furthermore, a senior manager from a construction company expressed the view that the proposed OCR has a very good application choice: because façade work is dangerous for human labour yet requires fewer skills than other trades, for example, welding or carpentry, the robot does not need to be equipped with a high degree of automation or sensors thereby making the price of the system potentially feasible.

Besides interviewing industry practitioners, the author conducted interviews with the Chief Technology Officers (CTOs) of two construction robotic companies. Both companies, from Denmark and Norway, are very close to full commercialization. Unfortunately, both companies wish to remain confidential.

The interview with the Danish company focused on the system application, product development, and business strategy. The CTO introduced the product application range and noted that it is important to develop a modular platform that can accommodate multiple functions and to label the system as multifunctional because it is equipped with an interchangeable end effectors, even though its multifunctionality can be deceiving. Effectively, it is still a single task robot, but under certain conditions, it could perform two entirely different functions at the same time. In fact, two types of construction tasks are rarely started simultaneously in one location; more often, there will be a waiting time in between the two tasks. He stressed that the initial product positioning strategy will directly influence the marketability of the final product so when considering which function to develop, the designer needs to investigate which tasks can be augmented by automation. The selected tasks are also better if they are based on the same plinth, plane, or angle to minimize the DOFs of the robot thereby reducing costs. The principle of allocation of function is also key to determine which tasks are worth automating and which tasks should remain manual. He emphasizes adapting the changes to market and customer requirements and a flexible business plan, which is why his company embraces customization and open-source software to increase product scalability.

The focus of the interview with the Norwegian company was to discuss technology innovations, operational strategies, business models, and recommendations for other start-up companies. The CTO admitted that the biggest challenge during the system development stage is trying to understand what the stakeholder requirements are as only listening to their comments or using a questionnaire is not enough: the best way to understand stakeholder requirements is to engage with the actual construction task and ask questions based on observations. He explained that the system needs to achieve short on-site set-up times, for example, the system from his company takes approximately 30 minutes to calibrate before the operation. He also explicitly explained that the company business model they are adopting is the rental model instead of the retail model because the company does not possess enough resources to offer after-sale services or training of operators. Most importantly, product reliability needs to be improved over time making it very risky to offer a product guarantee or warranty when the product may impose unforeseen challenges. Due to these, the company offers services to the contractors along with the OCR: providing training to the contractor, and offering maintenance, and repairing whenever necessary.

Regarding the type of certifications that are required, the CTO responded that it depends on how the OCR is pitched. If the OCR is categorized as a robotic system working on a construction site, then the certification procedure could be complicated due to a lack of regulation and certification system designed specifically for OCR implementation. On the other hand, if the OCR is classified as special construction equipment, then the system needs to acquire the conventional Certification of Electrotechnical Equipment and Components (CB) scheme, the CE marking, and to address the relevant Electronic Equipment Directives. As far as the CTO could recall, there is no specific certificate system designed for construction robotic systems. Moreover, he noted that it is challenging to obtain insurance coverage if the system is marketed as an on-site robotic system due to unknown product liability. This liability is a concern when adopting unproven technology or when the system of the existing construction method radically changes making it very difficult to gain professional and legal liability coverage from the insurance brokers. To speed up commercialization, it is therefore wise to pitch the proposed system carefully, but this, of course, depends on the policymaker and how strict the local regulatory system is. He advised that it is key to involve the customer and the key stakeholders from the beginning. When developing the system is it important to compare the weakness and strengths between humans and the robot and then decide the most appropriate system design.

Most of the interviewees acknowledged the potential of OCR, yet expressed concerns, such as high costs, unforeseen risks, and institutional uncertainty. While it is true that the implementation of automation and robotic technology in the construction industry is still at an early stage, the industry does believe that the development of OCR can bring positive outcomes to the industry in the future. Based on the previous investigation and interviews, there are a number of key barriers and drivers to the uptake of the proposed OCR technology.

4.5.3 Barriers and drivers to the market uptake

Following the investigation, the online surveys, the on-site case study, the co-creation workshops, and the interviews, the key barriers that influence the market uptake of the proposed OCR technology are:

- Technological barriers: even though automation and robotic technologies are well developed in other industries, there are very few automated or robotic parts, components, or integrated systems that are specifically developed for the construction industry. Due to the variation in working conditions between traditional industries and the construction industry, existing technologies might not be suitable.
- Economic and financial barriers: there is a lack of access to public funding that is specifically dedicated to OCR R&D. High initial development costs have a negative impact on gaining funding. In addition, to validate the design objectives, the system needs to be lab-tested as well as on-site field-tested, which increases overall development expenditures.

- Regulatory and legislative barriers: the definition of OCR is yet to be defined, so there is a lack of regulation, policy, and guideline coherence at the industry level. This leads to a lack of confidence to invest or use the proposed technology industry-wide.
- Market awareness barriers: as mentioned earlier, in general, the construction industry is not familiar with the proposed technology, neither the advantages it will bring nor the challenges that may occur. The construction market is hugely fragmented in terms of communication, collaboration, and motivation that may cause concern in terms of financial motives and operational objectives.
- Social barriers: the implementation of robotic technology and digitalization has profound implications for labour markets. One negative perception is that the robot will replace human labour and increase the unemployment rate. This topic was raised several times during the discussions with the Hong Kong labour department.
- Institutional barriers: the construction industry's current processes have well established but conservative supply chains and legislation, so any radical changes in practices may cause resistance from affected parties.

The key drivers are:

- Technological drivers: in general, the proposed OCR requires less precision than its industrial counterparts do. For instance, between 1cm and 3cm of deviation is acceptable due to the spray covering area. For this reason, most of the off-the-shelf robotic hardware and software are applicable for the system integration, but alteration would be needed to adapt to a construction application.
- Market demand drives: the construction market in Hong Kong faces a number of challenges, including an ageing workforce, the high cost of living, and increasing demand for public housing. The industry is aware of the challenges it is facing and eager to find feasible solutions. Many believe that automation and robotics provide one of the solutions.
- Institutional support: as mentioned earlier, the HKSAR, CIC and the private sectors have allocated significant resources and incentives to support I&T in the construction industry.
- Geographical benefits: Hong Kong is situated next to the PRD, which is the most economically dynamic region of Mainland China. Recently, Shenzhen has earned the nickname of the "Silicon Valley of China" with increasing R&D investment pouring into the areas of Artificial Intelligence (AI) and robotics. With the existing knowledge base and technical know-how, the collaboration between Hong Kong and Shenzhen can stimulate OCR development and establish a dynamic upstream and downstream industrial ecosystem.

4.5.4 Potential business model

The potential business model is based on the condition that either the CIC or an interested stakeholder will establish a spin-off company in the future. The spin-off company would focus on the development of the proposed OCR. The R&D facility would be situated in Hong Kong to secure IP protection while outsourcing to collaborators in the PRD region that would be in charge of manufacturing and supply chain management. For long-term projection, the spin-off company would gain profits through the following methods.

1. Retail: trading the multifunctional façade application robot, end effectors, components, and consumables for the construction industry.
2. Retail of the software application: trading the software application for customers as a system upgrade deal.
3. System integration: providing services for other companies that have a similar system or taking on R&D tasks based on a customer's demands.
4. Vocational training: providing training for prospective OCR operators, which can be achieved as a joint venture with the CIC.
5. Technical consultancy services: providing comprehensive technical services that focus on OCR development for the construction industry.
6. After-sale services and system iteration: repairing and maintaining the systems and offering replacement parts.
7. System rental: renting the system to contractors on a day-to-day basis with a daily-rate rental system or through a "pay as you go" model.

According to the investigation and the preliminary business model, a suitable spin-off company would be one that focuses on the rental market. For this project, the rental business model is different from a traditional rental model and would involve not only a system rental but also provide comprehensive services. The spin-off company would offer an entire array of professional services, such as on-site surveys, delivery, calibration, installation, operator training, and assisting the operator with the painting task. At the same time, this model would provide rapid repair services to ensure there would be no delay caused by a system malfunction. Alternatively, the spin-off company could employ skilled painters and offer the painting services, yet using the proposed OCR.

An example of a similar approach in practice, which closely resembles the proposed business model here, is from the GGR Group, a UK based company that supplies lifting devices, mini spider cranes, and other lifting solutions. The company owns the equipment and cranes but retails accessories, replacement parts, and consumables. Once the customer makes an inquest, the in-house engineers provide extensive consultation services and offer detailed lifting plans to avoid any complications during the operation. The customers are charged by a set price or daily rates. The company operates its own delivery fleets that cover a vast range of vehicle sizes and specifications, from vans to articulated lorries that provide system delivery, repair, and services. The company offers various ranges of training dedicated to different types of lifting equipment. The length of the training courses is between one and five days depending on the complexity of the equipment. The training takes place in the company training facility and is delivered by an experienced trainer. A successful trainee receives a Construction Plant Competence Scheme (CPCS) operator card issued by the National Councils for England, Scotland and Wales (GGR Group, 2019). Even though the products GGR Group offers are different from the proposed OCR, in the broadest sense, both can be classified as specialized construction equipment that general contractors are typically hesitant to buy but frequently rent. Consequently, the business model that GGR Group adopted can inspire the OCR business model development.

4.5.5 Summary

This section introduced the current support and incentive schemes offered by the HKSAR, ITB, ITC, private institutions, and the CIC that promote I&T activities in the construction industry. The market positioning was conducted using a number of matrices and comparing the proposed OCR against several perimeters, such as competitor competence, product user, usage, and attributes. The method was not only used to identify the prospective product position but also to classify different competitors based on the similarity of their market position. Comprehensive customer segmentation and value propositions were carried out to investigate who the potential customers are and how the market justifies the initial value of the proposed OCR. This exercise laid the foundation for the CBA, which evaluated the incremental costs and benefits, as well as the NPV, which was built on a value-based price method that calculated the estimated payback time. The CBA results were mostly positive but cannot be used as evidence to convince potential investors due to a lack of sufficient data. The potential business plan of how to promote the proposed OCR as a commercial product was also discussed. Four target markets, key barriers, and drivers that influence the future market uptake were identified and analysed. A preliminary business model was suggested based on an existing industry example to predict potential methods to generate profits and to identify what is the most appropriate business model for an early stage spin-off company. The discussion of the potential spin-off company marked the divide in the project from an academic research project into a product that will be commercialized. As noted, an exploration into how to transfer the proposed OCR from a conceptual idea into a marketable product and how to bring the product closer to the commercialization stage is an important step in the process. The transformation of research results into a market-ready product can take time and be very costly. The next section will evaluate how to identify various performance indicators for the proposed OCR within the defined operational and business environments.

5 Evaluation of the result

Transforming the proposed OCR from a research project into a market-ready product still has a long way to go, but it is beneficial to proactively look into what type of product KPIs are important and identifiable at the current stage of the project. This chapter will analyze how to predicate performance indicators while the system is still under development in order to recommend the methods to continue using for the remaining tasks based on the research results. This chapter will also present the forecasted risks and threats that will affect OCR development in the future.

5.1 Evaluation method

In the context of OCR, there is still no clear indication of how to identify the performance indicators or quantify how OCR satisfies the design specifications under working conditions (Lampe and Chatila, 2006). Measuring the performance indicators accurately is extremely important for each phase of product development. In particular, establishing a product performance indicator is crucial for product improvement and iteration (Echelmeyer *et al.*, 2011). The characteristics of the working tasks, environments, operator skillsets, and system specifications, as well as the requirements of the tasks, are fundamentally different between industrial robots and the proposed OCR. In the manufacturing industry, there are many KPIs used for mature robotic performance, yet those KPIs might not be relevant in the context of construction. Therefore, selecting quantifiable KPIs is key to improving system development. In this case, because the proposed OCR is still under development and the fully functional prototype is not scheduled to be built until the second phase of the project, there is limited data in hand and, therefore, difficult to conduct a detailed analysis of how to measure the performance indicators. Nevertheless, based on the experience of previous research and feedback from the stakeholders, in combination with the examples from the industrial robotics sector, it is feasible to outline the relevant parameters and variables that need to be taken into consideration when measuring the system performance task.

The relevant parameters are categorized based on the application and requirement areas:

Task-based parameters: This measures how the OCR specifications match the operational requirements. This analysis is based on the research method described by Bhanoday Reddy Vemula (Bhanoday Reddy, 2015).

- Job site: The assigned servo motors and the end-effector should be able to reach the specified façade areas. In particular, the paint nozzle needs to be able to provide consistent finishing quality.
- Flexibility: The OCR needs to be able to adapt to various public building façades, and the hoisting system should be installed on a common parapet wall without structural alteration. The dimensions and weights of the OCR need to be suitable for standard transportation loads as well as the load-bearing capacity of the building structure.
- Motion: In this case, the speed, trajectory, and position of the end-effector need to be either predefined before the on-site task or by using an onboard camera to capture real-

time images and through machine learning exercises, allow the robot to understand the real on-site environment. If using BIM data to predefine the travel path of the robot, it is important to compare the data with on-site survey data to avoid inaccurate data processing.

- Accuracy: In general, the end-effector needs to travel following the pre-programmed travel path, speed, and trajectory, unlike some manufacturing processes, such as tooling and material handling, which require a higher level of accuracy (Scheinman and McCarthy, 2008). The automated painting task may allow small deviations that can be compensated by the projection of the spray area. While sensors can increase operational accuracy, not every sensor is suitable to use on-site: sensors that are sensitive to lights, humidity, dust, and noise should be investigated to decide if it is suitable to be adopted in the specific conditions. In addition, for repetitive motions, the end-effector needs to return to the pre-programmed starting point after a task loop, emergency stop, or unexpected power cut.
- Reliability: The OCR needs to be designed to fit the harsh environment of a construction site. Weather elements and conditions, such as sunlight, temperature, rainfall, dust, and wind, need to be considered when selecting the hardware components. Precaution measures, rapid repair plans, and critical maintenance strategies are needed in case of system failure or damage.

Safety-based parameters: These are more practically relevant to OCR due to the unique circumstances of a construction site. Humans and robots often work side by side on construction sites and frequently have direct interactions (unlike the manufacturing sector where the robot is usually positioned in a safety cage, even though more recently, some manufacturing has introduced more human-robot interaction). Thus, the development of a collaborative robot shares valuable insights into how to manage intelligent assist devices (IADs) and physical human-robot interaction (pHRI) devices (Zinn, Khatib and Roth, 2004).

- Torque and speed: The torque and operational speed of the robot need to be carefully considered according to the specific task and under which conditions the task will be carried out. In this case, the desired hardware specifications and the impending control laws should be used to assist this issue. The speed of the robot needs to be negotiated so that the robot can safely stop under the influence of inertia in the case of an emergency.
- Protection: The proposed OCR can be classified as a fenceless robot, which means that the robot is not restricted in a safety fence and can move freely or be manipulated by the operator. Besides emergency stop functions, health and safety training should also occur. During the early design stage, the designer needs to carefully evaluate the allocation of functions to determine which high-risk decisions need to be made by the human operator and which types of lower-risk tasks the robot will take over.

Design parameters: With regard to OCR, the design requirements and the methods used to gain those requirements are inherently different from industrial robots.

- Flexibility: Flexibility can be understood from two dimensions: design flexibility, encompassing hardware and software, and operational flexibility. Design flexibility is closely associated with system compatibility, scalability, diversity of configurations, and the ability to adopt changes in design requirements as well as customer demand. The design process needs to follow an interactive approach that enables future improvements and interactions with the system without excessive redevelopment. Operational flexibility is the OCR needing to be able to adjust to the heterogeneous nature of the construction site without reprogramming or reengineering (Swevers *et al.*, 1997).

- Economic parameter: The construction sector possesses a low-profit margin when compared to the manufacturing sector (Akintoye and Skitmore, 1991). Therefore, the unit cost of the product is one of the key factors that can influence the confidence of the construction industry on whether to accept and adopt OCR. There are several ways to manage the cost. First, identifying the system specifications and the expected performance through cross-disciplinary collaboration between the researchers and the industrial partners. Second, based on the requirements, utilizing off-the-shelf products instead of reinventing the wheel. The optimal payback time for the system should happen within three years.
- Soft factors: The construction industry is conservative as it tends to resist any rapid or radical changes. Consequently, OCR development should be an incremental process. It is often recommended by industry practitioners that the early OCR generations be compatible and comply with the existing working methods, materials, and institutional requirements. In addition, the focus should not be on how to increase the automation level of the system nor on how to replace human labour entirely but instead on how to apply the right amount of automation to augment human performance and improve construction productivity and safety.

Efficiency is one of the key parameters that determine the performance of the OCR. Because efficiency can only be measured once the OCR has been commissioned and gone through the future pilot project, there are some key factors that should influence system operational efficiency.

1. Downtime: Time is money; as true for the construction industry as any other industry. Downtime can occur because of equipment failure or inadequate management (that makes OCR redundant). The methods to reduce downtime include regularly and proactively maintaining the system, regularly backing up the system, and providing targeted training to the staff. In addition, being aware of the availability of OCR and continually assigning tasks to the robot will help avoid system redundancy.
2. Complexity: Avoiding complex hardware and software composition and integration will make repairs easier and the likelihood of malfunction decrease dramatically. Consideration of whether a specialized service or other attention is required when the OCR enters faults. If needed, is it easy to allocate local engineers to be present on-site or can the issue be addressed via long-distance communication?
3. Setup times: The construction project often follows a very tight schedule and therefore keeping a minimal setup time is vital. Setup activities can be classified into two levels: preliminary set up – system installation and calibration amongst system arrival – and reallocation – dismantling, decommissioning, and relocating to the next job site. It is

better if the system design effectively reduces the time spent on installing temporary fixtures or building alterations prior to system installation.

4. Training: The proposed OCR has never been adopted in the construction sector so there are limited operators available on the current market. In fact, the industry lacks experienced engineers, operators, qualified trainers, and other supporting roles. Offering a reasonable training time will have positive implications for the conditional acceptance of the system. For example, depending on the specific topics, training should last between 1 and 5 days. In terms of training operators, it is best to consider combining existing gondola and painter training programs with the OCR training as an additional training module so that the existing training facilities, resources, and regulations can be fully utilized.

At the time of writing, it was still too early to identify the specific KPIs for the proposed OCR. Nonetheless, this section provides preliminary insight on which relevant parameters need to be considered during early OCR development phases. To gain accurate and appropriate KPIs, a large number of tests, calibrations, improvements are unavoidable.

5.2 Adoption strategy

Phase two of the CIC project is currently on hold because the CIC would like to encourage local construction practitioners to share more of the commitment and risks and to participate in the phase two project proactively. The predicament for an academic partner such as TUM is that while the university is capable of conducting the initial research and providing a PoC, a proof of principle prototype, or a mock-up, the university is not able to deliver a working prototype or functional prototype without collaboration with industry partners due to liability issues. For instance, to conduct a comprehensive pilot project, the proposed OCR would need to be installed on-site and tested thoroughly under all weather and working conditions. In the case of an unexpected or unpredictable event, the university would be unable to cover personal injury or fatal incident reparations caused by the system (either through personal misconduct or system malfunction). Therefore, even though the university ensures the delivery of a PoC, it cannot guarantee the functional performance of the OCR. In principle, it is preferable to establish a startup entity and to continue pursuing the goal of creating a market-ready product. The startup entity could be initiated by the CIC, the industry partners, or, alternatively, the existing project team members. The following section will demonstrate how to establish a startup company based on the existing outcomes from the CIC project.

Creating a startup specializing in a multifunctional façade finishing robot will require the following steps.

Step one: Establishing a strong professional team that can be fully committed to the potential business proposition. The individual co-founders will need experience in various disciplines, such as informatics, mechanics, marketing, and administration. Moreover, connecting with a business mentor as well as technical advisors can be beneficial in the early stages of business development.

Step two: Structuring a clear business model, specifying the brand image, targeting and segmenting customers, proposing product values, and formulating a short- and long-term business plan. These topics exhaustively in chapter 4.

Step three: Establishing a legal entity, such as a limited company (LC), to avoid being personally liable for potential legal accusations as well as registering with the local tax office, opening a business bank account, and securing any relevant business insurance.

Step three: Developing a working prototype or, if there is a lack of funding, developing a scaled prototype combined with a self-explanatory visual prototype will be highly beneficial for the next stage.

Step four: Approaching potential investors from both the public and private sectors that are interested in the business filed. The funding sources may be from different countries (the available public and private funding sources in Hong Kong are described in detail in chapter 4.

The scenario above only presents one possible approach, but the final execution of the adoption strategy will depend on where the startup entity is established the financial situation and the team composition.

5.3 Critical risks before and after commercialization

The completed phase one CIC project has used a persistent and incremental approach to development to demonstrate to the Hong Kong PHC sector how to bring an OCR from a conceptual idea to the proof of principle mock-up stage. In terms of system development, to avoid some of the critical risks being overlooked, it is necessary to outline them in the early stages.

After developing the PoC and moving towards the product market uptake stage, the next step is to secure an investor. The prospective investor will need to evaluate the potential risks and profit margin of the business and usually requires a detailed CBA, a business plan, and other tangible supporting data. Gathering this data can be capital intensive, and in this case, the funding has not yet been secured, and providing tangible evidence or reference cases will be difficult until the proposed OCR is thoroughly tested. One of the biggest risks for the project is that an investor may not be fully convinced by the visual stimulation and the demonstration mock-up.

If the startup secured sufficient funding and started trading, then the following nine potential threats and risks would need to be easily recognized, and feasible measures should be prepared in advance.

1. Intellectual property protection risks: There is a possibility to collaborate with companies in mainland China due to manufacturing capacity and cost advantage. However, this type of collaboration may be subject to the risk of intellectual property infringement. The response measures should include obtaining strong legal backup and advice coupled with accelerating iterative cycles of product development.

2. Obsolete technology risks: After the product release, the technologies used may become obsolete and replaced by advanced technologies, so companies should continually increase R&D efforts, develop new products and services to maintain the business's competitiveness.
3. Price risks: The initial price of the proposed OCR may be higher than the market expectation due to an immature supply chain. In order to match the expectation of the market, a discount sale or a no-profit sale could be enforced to gain market recognition and market performance. As a solution, the company should diversify their products and services to optimize product layout and technical specifications and adjust company strategy in a timely manner.
4. Marketing strategy risks: Inadequate marketing strategies can lead to unsaleable products and loss of profits and customers. A well-planned and adaptable marketing strategy are vital, thereby requiring that the marketing manager be experienced in a similar field.
5. Production risks: Due to the unfamiliarity of the proposed technology, early production may face certain difficulties such as inconsistent product quality, long component ordering times with long production cycles. The feasible countermeasures include keeping the design simple, utilizing off-the-shelf products, and selecting reliable and experienced system integrators.
6. Financial risks: A lack of funding will have negative implications for daily operations, R&D efforts, and other expenses. The management should reduce expenditures, actively seek out government financial incentives, apply research funds, reduce operational costs, and reduce financial risks of product development.
7. Managing risks: The management team may not be aware of the market, technology, or other relationships between key stakeholders, thereby leaving management philosophy possibly out of touch. All viable solutions use the existing industries as a reference to train the management team and to enhance the core competitiveness of enterprises.
8. Policy risks: Real estate development can affect the progression of the construction industry. The existing building regulations and health and safety policies may either drive or hinder the OCR implementation. To keep the business sustainable, the appropriate measures will consist of keeping up with the existing policies and paying attention to prospective policies.

5.4 Summary

This chapter introduced the relevant parameters used to measure the expected OCR performance indicators. They are expected performance indicators because at the time of writing it is too early to identify specific KPIs for the proposed OCR. The pre-identified parameters include task-based parameters, safety-based parameters, design parameters, and efficiency-related parameters. Next, the aspects that need to be taken into consideration and the four steps of how to establish a startup entity to continue the development of the proposed OCR will be outlined in addition to demonstrating the potential risks and threats as well as feasible solutions prior to and after the market uptake. This chapter will provide valuable insights on how to bring the current research results to a market-ready product, which will proactively prepare a realistic plan for future development.

6 Roadmap and guidelines development

This chapter will present a generic roadmap that demonstrates the tasks, milestones, and goals involved in OCR development. The roadmap helps lay the foundation for formulating the comprehensive guidelines regarding how to implement OCR for the Hong Kong PHC sector. The guidelines are based on the CIC project, which was divided into eleven stages, and describe the project tasks and objectives sequentially. The recommendations section focuses on the project from the initial research stage to the mock-up building stage and suggests aspects that need to be taken into consideration while carrying out the tasks. In addition, the lessons learned section describes the insights gained from the CIC project as well as the knowledge accumulated through the doctoral research that should be taken into account in future projects.

6.1 Roadmap

This section will provide an overview of the roadmap's development based on the experiences gained during the current CIC project. It seeks to provide a comprehensive roadmap for developing the OCR application by demonstrating the tasks, milestones, and methods that will be used to solve data collection, initial research, technological, operational, economic, and institutional problems. The outcome of the roadmap will be a beginning draft of the design guidelines to assist public or private parties in preparing or conducting similar projects.

The generic roadmap in Figure 102 describes the main tasks, milestones, and critical goals that the OCR development will face after consulting the potential investors and taking the advice given by the industry practitioners. The overall development duration of the roadmap is set at three years (36 months) and is divided into three milestones. This roadmap is only for demonstration purposes and is only being used to illustrate the principle composition of task allocation within the three year period. The final practical roadmap will need to be drafted after close collaboration between the development consortiums, stakeholders, and public bodies.

Before jumping into the detailed task description, a brief explanation is provided to assist the audience in reading the roadmap: the top grey bar indicates the time span; the 12th, 24th, and 36th months are highlighted in black; the topics of the tasks are located to the left; the blue arrows represent the time span of the specific task; the red dotted lines indicate the milestones; the small green boxes with a red outline are the critical goals that determine whether the project will be terminated or continued based on the proposed strategies.

The detailed task breakdown in each project stage is described below.

Project planning and preparation: For this, it is assumed that a legal entity, such as a start-up company, is already in place. The sub-tasks involved in this stage are:

- To identify research gaps, project scopes, and objectives and to analyze the current resources and competence
- To conduct the initial project planning and to evaluate the feasibility of the project
- To predicate the potential risk factors and to develop appropriate mitigation strategies and contingency plans

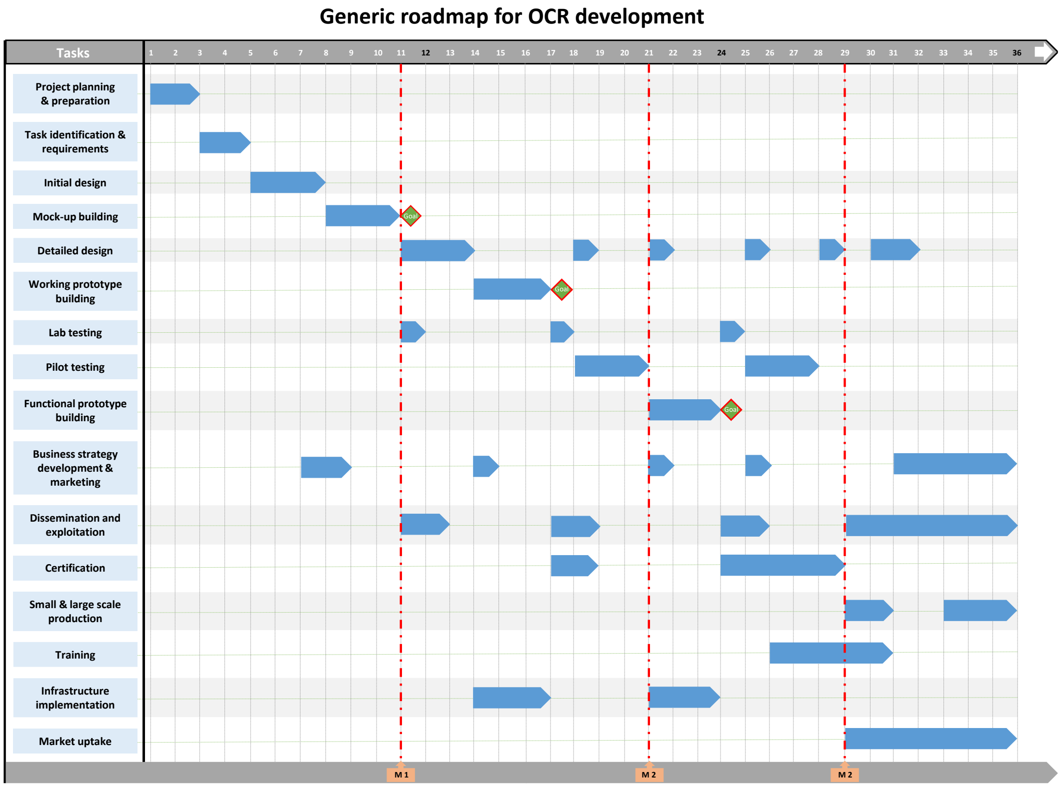


Figure 102: Generic roadmap for OCR development.

Task identification and requirements: This stage contains some key activities that will determine the final project scope and define the initial requirements of the final OCR product. The sub-tasks involved in this stage are:

- To conduct surveys, on-site visits, and co-creation workshops between the design team, key stakeholders, and industry practitioners
- To determine which task or part of the task is worth automating, to define the appropriate allocation of function, and to define what is the optimum level of automation to apply
- To draft the system requirements and to develop the initial value proposition based on the identified requirements

Initial design: During this stage, the basic design details will be developed according to the defined requirements and the initial research. The sub-tasks involved in this stage are:

- To draft the conceptual design of the system and to define the initial function, application, and dimension
- To produce technical drawings as well as digital and physical mock-ups of the proposed product
- To conduct the initial simulation under the selected software environment
- To collect necessary information regarding the off-the-shelf components, parts, materials, and potential system integrators

Mock-up building: This stage unfolds the first milestone so it is critical that the design team is in a position to produce the mock-up. The sub-tasks involved in this stage are:

- To work closely with the selected system integrator if the company does not hold mock-up building capability
- To produce a scale mock-up, of which the scale needs to be suitable for the purpose of the mock-up
- To plan system optimization and iteration strategies based on the mock-up

Detailed design: This stage is an incremental process, which will be carried out after the mock-up building, lab testing, pilot testing, and certification stages, to continually improve the system design. The sub-tasks involved in this stage are:

- To design the final system based on the feedback gathered from the previous research and the mock-up
- To design hardware and software of the product and to provide feasible integration and iteration strategies
- To produce the final technical documents, to formulate the product specifications, and to make sure the data is ready to pass on to the system integrator for the prototype building
- To establish an IP management plan
- To optimize the system after the mock-up building, lab testing, pilot testing, and certification stages

Working prototype building: This stage showcases an important critical goal the project needs to achieve, which determines whether the working prototype is ready for the purposes of convincing potential investors and evaluating the assigned functions. The sub-tasks involved in this stage are:

- To produce the working prototype closely with the system integrator and the key stakeholders
- To estimate the initial cost and producibility of the final design
- To evaluate the availability of the suppliers and to develop a procurement strategy
- To test the initial function and performance of the intended design
- To prepare the supporting data required by the testing, dissemination, and certification stages

Lab testing: A succession of laboratory tests will be carried out on three separate occasions: one after the mock-up building, the second after the completion of the working prototype, and the last one after the functional prototype is constructed. Usually, the prototype will be tested under laboratory conditions before being sent off to be pilot tested on-site. Therefore, testing under a controlled environment will ease the system calibration, fault detection, and improvement. The sub-tasks involved in this stage are:

To prepare the testing facility

- To conduct relevant tests required by the upcoming pilot test or by the certification organizations
- To test the functional prototype and to document any system alteration or improvement tasks that need to be assigned to the design team

Pilot testing: This stage marks the second milestone of the project and it is extremely important that OCR is tested in a real construction environment. The sub-tasks involved in this stage are:

- To secure and prepare the testing site
- To test the functions, hardware and software integration, electronics, and mechanics of the intended design under various on-site conditions
- To develop an operation manual
- To develop health and safety measures
- To decide which KPIs need to be tested on-site
- To recommend a system optimization plan for the design team
- To conduct the second-round pilot testing after the completion of the functional prototype
- To collect data that will support the business model, marketing, and training activities

Functional prototype building: Building a fully functional prototype is another critical goal during the project. The functional prototype will demonstrate the final function and performance of the intended design. The sub-tasks involved in this stage are:

- To produce the fully functional prototype according to the feedback from the pilot testing
- To verify the proposed system performance
- To prepare the system for small scale production
- To collect data required by the certification protocols, business model development, and infrastructure implementation
- To verify the system KPIs in conjunction with lab testing

Business strategy development and marketing: Business and marketing strategy development is integrated into the system design from an early stage of the project and is spread over initial design, prototype building, and pilot testing stages. The sub-tasks involved in this stage are:

- To identify both "soft" – people, attitudes, emotional feelings, and intangible elements – and "hard" and tangible – cost, speed, quality, and financial benefits – elements of the project.
- To conduct detailed market positioning analysis
- To conduct a detailed value proposition and to define target customers
- To conduct CBA analysis
- To develop applicable business strategies and marketing plans

Dissemination and exploitation: This stage aims to distribute relevant information to specific target groups and is crucial for disseminating the product outcomes to the desired audience. The dissemination activities will be carried out incrementally according to the availability of project results. The sub-tasks involved in this stage are:

- To identify key stakeholders, customer segments, and target groups
- To define which type of dissemination activity is effective for reaching a specific audience
- To develop effective communication strategies
- To conduct the planned dissemination activities
- To promote the product image and raise public awareness

Certification: Securing appropriate certification requests by the construction industry is one of the key milestones that the project faces. It is the basic legal requirement that determines if the proposed product can be commercialized. The sub-tasks involved in this stage are:

- To contact the organizations and authorities who deal with construction equipment certification; this can be done shortly after the working prototype is completed
- To verify if there are additional standards or certifications with which the proposed system needs to comply
- To position the product in an appropriate market category to eliminate additional legal requirements

Small and large-scale production: This stage aims to verify the producibility of the final product and estimating the investment requirement for full-scale mass production. The sub-tasks involved in this stage are:

- To contact manufacturers that are capable of producing the product
- To conduct quality inspections
- To investigate if there is room for improvement in terms of design, function, and performance
- To identify reliable suppliers that are in a close range of the planned operating area

Training: OCR technology is relatively new to the construction industry; therefore training prospective operators, engineers, and support personnel will have significant positive impacts on the commercial implementation of OCR. The sub-tasks involved in this stage are:

- To evaluate which types, if any, of existing training programs are relevant to OCR
- To contact the government training body or any other training provider that already offers the relevant training
- To plan the initial training materials and prepare the training facilities alongside the selected training provider

Infrastructure implementation: The existing construction industry lacks the infrastructure that would ease OCR implementation. The main activities in this stage will be carried out shortly after the detailed design stage and continue through the pilot testing stage. The sub-tasks involved in this stage are:

- To identify areas in the construction site where there is a lack of OCR-friendly infrastructure
- To verify the infrastructure upgrade strategy for the proposed product
- To recommended feasible and incremental adaptation strategies to the construction industry where there are existing infrastructures that need to be altered

Market uptake: This stage starts after the certification stage and is an important step for indicating that the proposed product is ready for market launch. The sub-tasks involved in this stage are:

- To formulate a market launch strategy and communication plan
- To plan post-production, after-sale service, repair, and maintenance strategies
- To strengthen the existing collaboration and to expand the future networks

The section above introduced the comprehensive generic roadmap with a detailed task breakdown in each project stage to explain the vital goals and milestones for OCR development. The roadmap serves as a foundation for developing the design guidelines.

6.2 Guidelines

This section presents the key output of the dissertation: the comprehensive guidelines regarding how to implement OCR for the Hong Kong PHC sector. As discussed earlier, bringing an OCR from the research stage to near-market uptake stage is an incremental process for which the guidelines provide an overall insight. The guidelines were developed based on the multifunctional façade finishing robot CIC project. Even though it is based on the circumstances of the Hong Kong PHC sector, the highlighted systematic methodological approach could also work in a similar project. The guidelines separate the development process into specific tasks that are similar to the roadmap, see Figure 103. In addition, they describe the objectives of the tasks, recommend the appropriate actions and methods, and explain the lessons learned.

6.2.1 Detailed task breakdown and objectives

The OCR development has been divided into eleven stages, see Figure 103. The main focus will be on the phase one part of the CIC project and will emphasize the tasks involved within the first four stages (these stages are highlighted in the lighter blue section of Table 53).

Table 53: Detailed task breakdown and objectives.

Project stages	Sub-tasks	Objectives
1. Initial research	• Project induction • Elementary overview • Literature review • Brainstorming • The preliminary goal, scope identification • The initial stakeholder identification and requirements identification	To understand the project brief and requirements and predicting the potential outcomes. To allocates roles and defines responsibilities amongst the project partners.

2. Survey & detailed research	• Stakeholder analysis • Online survey • Interviews & questionnaires • On-site case study • Co-creation workshop	To identify stakeholders, primary requirements, and priority areas and to define the purpose and functions of the proposed system. To familiarize the development team with the existing construction methods.
3. Initial design	• Conceptual development • Allocation of function and automation identification • Primary design • System configuration design • Initial operational process analysis • Supporting system development • Software & hardware integration planning • Product iteration planning	To define which functions should be automated with which type and level of automation. To determine the initial kinematics, configuration, functions, and working process of the proposed system. To provide PoCs that verify the initial design that will be used for other key development tasks.
4. Mock-up building	• Digital mock-up building • Small scale physical mock-up building • Interactive mock-up building • Verify PoCs of the proposed system	To validate design concepts and system functions, which will be highly beneficial for the fully functional prototype. To create a mock-up for disseminating early project results.
5. Detailed design	• Prepare the final design documents • Produce an inventory list for the final components, parts • IP application, if necessary • Iteration planning • lifecycle management strategy	To complete the final version of the design once the design data is ready to be distributed to the relevant stakeholders and the proposed system is ready for prototyping.
6. Prototype building	• System refinement • Identify relevant tangible data	To verify system design, function, and performance through the prototype. To gather tangible data that can be used for system testing, specification development, marketing, and system improvement.
7. System lab testing	• Accuracy check • Control system test • Performance validation • Repeatability test • Damage test, if necessary • Safety test • Maintenance strategy	To check the absolute accuracy, repeatability, reliability, and safety of the system against the assigned tasks under the lab testing environment.
8. System pilot testing	• Function test • Performance test • Reliability check • Usability test	To validate the system performance, dependence on weather, and operator skills. The pilot test results can be used to develop the system KPIs.
9. Business model development	• Market positioning • Customer segmentation and value proposition	To determine which business model is applicable to the proposed system. To investigate how to gain support and incentives through public or private channels.

	• Available incentive and support evaluation • The detailed market analysis focuses on business model implementation	
10. System finalization	• System certification • Training • System improvement • Small-scale production	To acquire relevant certification for the proposed system and to train the operators so that the proposed system is ready for market launch.
11. Dissemination & exploitation	• Information distribution • Promotional • Knowledge, skill transfer • Communication	To disseminate tangible and intangible outputs of the project and to disclose the results to the right parties by appropriate means.

A brief description of the remaining tasks will follow, but because these tasks had not been conducted by the time of this writing, they are only summarized. Generally speaking, once an entity, whether that be a private start-up company, an existing company, a government research institution, or a university, is willing to deliver an OCR from the conceptual stage to the demonstrator stage, it can follow the guidelines provided (Pan *et al.*, 2019). The information on the recommended methods and lessons learned will be visited in the later sections.

1. The development team needs to conduct its initial research based on the project scope. The sub-tasks that belong to the initial research include project induction, elementary overview, literature review brainstorming, defining the preliminary project goal, and defining the initial stakeholders and requirements. The objective of this stage is to provide basic project requirements that serve as an introduction for the involved project partners to brief them about the given task. During this stage, the project development team should be well informed regarding their roles and responsibilities. In addition, an exclusive introduction will be offered to the partner who is not familiar with the proposed technologies to ensure everyone has achieved the same level of understanding about their specific roles and contributions.

2. Based on the initial research, at this stage, the development team should have a brief understanding of the project requirements and, therefore, be able to conduct data acquisition tasks according to the deliberate target groups. The sub-tasks include stakeholder analysis, on-line surveys, interviews, on-site case studies, and co-creation workshops. The objectives are to identify the key stakeholders, priority areas, or specific tasks that are worth automating and to verify functional and non-functional requirements as well as being fully aware of the existing construction methods used in the tasks that are intended to be automated.

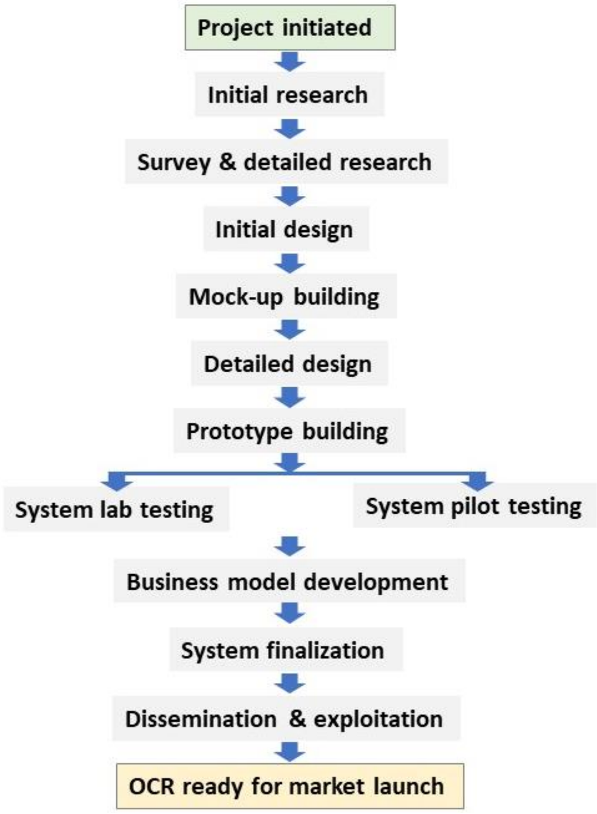


Figure 103: Detailed task breakdown.

3. Based on the findings from the previous stages, the development team can begin with the initial design of the proposed system. The sub-tasks consist of conceptual development, allocation of function and automation identification, primary design, system configuration development, initial operational process analysis, supporting system development, software and hardware integration planning, and product iteration planning. This stage aims to define the initial software and hardware design, primary functions, and performance checks that provide PoC insights for prospective development. The initial design stage contributes key inputs for the mock-up building, business model development, and detail design stage.

4. Supporting the design decision requires using models and mock-ups. The model types include computerized digital models, scaled physical models, and an interactive mock-up. The main objectives of the models and mock-ups include enhancing the virtual interpretation of the concept, providing a cost-effective way to verify various design features such as kinematics design, software and hardware integration, and mechanical composition. In addition, the mock-up is an effective dissemination tool that can be used to increase public awareness and to attract further investments.

5. At this stage, the project enters the detailed design stage. The development team will prepare the final design documents, which may include CAD drawings and an inventory

of the components, parts, and final specifications. This stage will prepare technical information for prototype building, IP application, certification, and business model development. In addition, a detailed iteration and lifecycle management strategy will be developed. There are only limited design alterations that will take place after the detailed design stage assuring that the design is now close to the final stage.

6. Prototype building refers to the construction of the functional prototype and marks the pinnacle of the project that indicates the prototype can now provide tangible data for marketing, testing, and design improvement.

7. System lab testing consists of hardware and software calibration that determines the system's functionality, accuracy, safety, and reliability. This step is an important stepping-stone towards the real applicative works on the construction site.

8. System pilot testing aims to check the intended functions, performance, and reliability of the system under on-site conditions. The outcomes can be used to determine the final KPIs and to validate the final design and means that the system is one step closer to the final product launch after a successful pilot run.

9. In terms of business model development, the sub-tasks include determining the market position, customer segmentation, and value proposition of the product. This also includes investigating the local incentives provided by the government or private sectors and conducting a CBA based on the available data. In addition, it must reference the existing product or the competitors' product that shares a similar market sector and business model.

10. System finalization consists of the following sub-tasks; system certification, operator training, system improvement, and small-scale production. The completion of this stage suggests that the proposed system is ready for market launch.

11. The dissemination and exploitation stage focuses on identifying the target group and determining which are the best methods for distributing information, attracting the interests of the key stakeholders, and increasing the impact of the project outcomes.

6.2.2 Recommended actions and methods

This section will focus on the first four stages of the OCR development: the initial research, the survey and detailed research, the initial design, and the mock-up building. Because this is also intended for any project that shares a similar goal as the CIC project, the analysis is quite general so that the recommendations can be used for universal purposes. Instrumental recommendations will be made on how to conduct an initial CBA in the early stages of OCR development, prior to any tangible supporting data being available.

The initial research is the first stage as well as one of the most influential stages that can determine whether the project is on the right track. The primary goal during this stage is to clarify the project objective, scope, duration, funding, and other resources to make sure the intended tasks are feasible. The involved parties should understand the context of the project and what is expected of them in the early stages. Based on the project brief, introduced by either the client or the project manager, the development team can conduct the initial research accordingly. The methods for the initial research are based on qualitative research principles, which aim to explore the given topics and to establish hypotheses through holistic analysis and focus group brainstorming. By doing so, the development team will gain an understanding of what to develop, what issue the product will address, who the potential end-users and stakeholders are, and what kind of products have been developed in the past that can be used as a case study. In addition, the answers to these questions will assist the development team in formulating the key features of the proposed product.

The survey and detailed research stage is part of quantitative research. During this stage, the priority is to identify the key stakeholders because the construction sector contains many stakeholders who have explicit interests and objectives concerning the expected outcomes of the project. Therefore, understanding the relationship between the project and each individual stakeholder can help narrow down the target group and verify the stakeholder categories, classifications, disaggregation, dispositions, requirements, and potential impacts on the project. This can then help in understanding the precise functional and non-functional requirements of the key stakeholders. A detailed description of how to conduct stakeholder analysis in the CIC project was illustrated in chapter 3.

Additional to stakeholder analyses is collecting data from specific subject groups. The main objectives of the data collection are being aware of what the stakeholder's attitude is towards OCR, identifying the target group, and understanding how to encourage their involvement while also mitigating contradictory interests related to the proposal. In the CIC project, there were three data collection methods used, including on-line surveys, on-site case studies, and co-creation workshops. The optimum method can vary from project to project depending on the project budgets, time scale, and access to subjects or information. The biggest challenge the CIC project team faced during the data collection process was that the subjects could not relate the proposed technology with their own experiences. because of this, the author produced a booklet whose contents had comprehensive information regarding construction automation and robotics. The purpose of the booklet was to introduce the proposed technology to an audience that was hearing about OCR for the first time. The development team did need to know which data collection method was appropriate for different subjects. Based on the experience gained from the CIC project, the electronic survey is more suitable for managers or people in higher-ranking positions due to its being more time-efficient and its ease of completion (Kannan, Chang and Whinston, 1998). Unfortunately, the response rate of the survey was low and the credibility of the answers was questionable due to distractions caused by other work tasks and possible unwillingness to complete the survey. If it is feasible, combining an online survey with a telephone follow up interview is highly recommended for achieving the optimum results.

Furthermore, it is highly recommended to conduct an on-site visit during the data collection stage. The on-site case study provides a unique opportunity to not only raise questions but also engage in the actual construction task. Through observation and interviews, it is possible to gather first-hand information regarding construction issues and concerns that the front-line workers face daily. The objectives of the co-creation workshop are to narrow down priority areas and to evaluate the project from each participant's perspective. It is an effective method for establishing a transparent overview of the project, but the preparation, participant selection, and invitation processes can be time-consuming. Thus, if the project is under a tight deadline, or the organization has limited resources to disburse, the co-creation workshop featured in chapter 3 can be substituted with a collection of brainstorming sections.

At the beginning of the initial design stage, it is vital to verify which tasks should be assigned to a robot and which tasks should be assigned to a human, or alternatively to apply the pHRI approach. To make the correct decision in regard to the allocation of function for a specific task, the design team must understand the existing working methods, procedures, and protocols as well as which dynamic physical body movements are associated with the task. The design team must also understand the type of conventional tools that are used and then evaluate the level of health and safety hazards imposed by the task. The task needs to be analysed systematically to understand what the core performance is and then the competencies and constraints of a human worker for each step of the task. First, the task needs to be divided into subtasks while the roles that human plays in each subtask is analysed. Based on the roles that human plays, the limitations, and constraints associated with the specific task will be identified. The parameters that can be used to assist in this exercise include asking whether the task involves sensing, information processing, decision-making, controlling, and whether the task is repetitive, dangerous, and costly. The parameters above provide a coherent insight into human involvement in certain tasks.

Information processing capabilities can directly influence the complexity of the proposed system and have huge implications for the feasibility of the product. Most construction tasks consist of consistent information processing activities, such as data based on the worker's training or previous experience. The most popular on-site data transfer methods are through verbal and written communication. The design team needs to investigate how humans collect, process, and distribute information in comparison to an automated manner. In fact, to keep the proposed product economically viable, it would be nearly impossible to fully automate the entire information processing sequence. Subsequently, some information processing steps, such as decision selection, especially in high-risk tasks, still require extensive human interference. The comparison provides a foundation for deciding what is the optimum level of automation to be applied for the task.

The initial development phase includes making sure the design is robust and can handle the on-site conditions. The system needs to be designed to offer maximum openness and flexibility, which can ease iterations, repairs, and maintenance (Brugali *et al.*, 2010). The product needs to be transported by conventional means of transportation, to have a fast installation time, and to not cause any destruction on-site. The system also needs to be compatible with the existing building structure to minimize installing temporary support structures or amending the existing building. To achieve both technological and economic feasibility, it is better to develop and position the initial system close to a piece of construction machinery rather than a robotic system. The advantage of this strategy is that the system is unlikely to provoke radical changes in the conventional construction sector since it is adaptive in both technical and institutional aspects thereby not overwhelming the construction industry with the proposed technology. In contrast, if the initial system were developed as a robotic system, with no adequate infrastructure, regulation, or certification system in place, there would be a slowing down in the market uptake speed. With the right levels and choices of automation and pHRI, and, most importantly, if the design satisfies the client's requirements, then reducing design specifications will make the system more practical.

There are three main purposes for making a mock-up. The first is to use the mock-up to visualize the concept. The second is to verify the system feasibility with respect to mechanical, kinematics, and hardware and software integration. The third is to use the mock-up as a demonstration for dissemination purposes. In general, digital mock-ups are often used for concept visualization and can be produced in a variety of formats, such as image, stop motion video, animation, which depend on the individual organization's preference. The physical mock-up is also an effective way to examine complex movements and mechanical features without spending a large number of resources to produce the realistically sized prototype. When developing the demonstration mock-up, there are many aspects that need to be taken into consideration: the design team needs to work closely with the manufacturer to offer advice when necessary; the size and function of the mock-up need to be decided upon based on the final demonstration purpose; even though at this stage the mock-up is only a demonstrator, less improvement and iterations will save time in the future; and, if the same mock-up can be reused when building the working prototype, it will potentially save costs.

The client or the potential investor often request a CBA in the early phases of the OCR development. They will expect the design team to quantify the benefits of the proposed system in monetary terms, but this quantified data cannot be confirmed until the fully functional prototype is tested. The clients or investors typically have limited knowledge about the proposed OCR so they often rely on previous experience from other sectors, such as the manufacturing or automotive industry. Because those industries are well-established, much of their cost data is available. Unfortunately, there are very few examples that can be used as a reference for OCR. Based on the experience gained from the CIC project, combining NPV and CEA is one of the viable solutions, especially for an early-stage CBA estimation while the proposed OCR is still under development. The advantage of the NPV method that was introduced in chapter 4 is that the data required for the calculation is available and accessible in an early development stage. The only assumption that needs to be made is how many labourers the OCR would be able to upskill. Nonetheless, after the initial design phase, the development team should have sufficient information to make a convincing argument about labour-saving.

6.2.3 Lessons learned

The CIC project provides an opportunity to look over how to bring a research project related to OCR technology from a conceptual idea to the demonstration stage. With sufficient funding, the proposed OCR will be finalized and pilot tested, which will increase the chance of market uptake. The experience gained from the CIC project is extremely valuable as it demonstrates the opportunities as well as challenges of implementing robotics and automation technology in the conventional construction industry. In this section, the lessons learned from the CIC project are enumerated, particularly those factors that could contribute to potential success or failure. In addition, the ROD concept will be evaluated based on specific scenarios.

According to previous research, many construction tasks can be automated, but the high level of automation and the complexity of the system are often not economically justifiable. Therefore, it is crucial to verify product performance and set up clear design goals with the key stakeholders. In a well-established industry, such as the manufacturing or automotive industries, the clients can specify their requirements and set high expectations for the final product. Regarding OCR, neither the customer nor the development team can define the system specification or expected performance due to a lack of available references. Thus, cross-disciplinary collaboration is a rudimentary requirement for the success of any OCR project. Because the construction industry consists of many stakeholders, one of the hurdles is addressing their requirements and translating their requirements into the design. In the previous chapters, methods of conducting stakeholder analyses and using the collected data for making decisions during the initial design process were introduced. There are various attributes that hinder or indirectly prevent OCR adoption taking place, see Table 54.

Table 54: The attributes that hinder or indirectly prevent OCR adoption.

Attributes	Description
Conflict of Interests	The statistics that measure the success factors of the OCR project might not represent all stakeholders' interests. For example, a goal of labour-saving could trigger a conflict between the labour department and the proposed OCR.
Hierarchies	The construction process is divided into subtasks that are managed by different contractors. Therefore, it is difficult to define which party will be the main beneficiary of adopting OCR. The liability of the contractor is protected by mainstream legal systems, but when introducing an innovative system, the contractor faces the risk of not being protected by insurance. Because conventional insurance providers are resistant to unconventional methods. In addition, it is often difficult to install or alter any completed building work to facilities OCR.
Resources	A larger organization may have sufficient funding for workshops and strategy development, but without any incentives, SMEs may not be motivated to carry out such activities. The feedback from SMEs is therefore highly relevant because the end-user of the OCR is more than likely to be SMEs.
Resistance to change	The construction industry relies on well-established supply chains, regulatory systems, professional services, procurement systems, and legal protection (Winch, 1998). The industry is resistant to change and does not encourage new ideas or the adoption of new technologies. This attitude inflicts negative outcomes on the fundamental value of ROD.
Openness	The construction industry does not share a high level of enthusiasm for learning, open discussions, and collaboration. Many construction data is strictly confidential and not accessible from project partners or researchers.
Short term vision	As mentioned earlier, the average development duration for an OCR is three years and this is a conservative estimation because, in a complex system, the development time can be even longer. Construction companies are project-based organizations, and therefore, the organization only focuses on short-term goals and is usually unwilling to engage in a long-term commitment.
knowledge base	To successfully develop and launch an OCR requires cross-disciplinary collaboration, but the collaboration needs to be supervised by someone or some organization with proficient knowledge in all relevant fields, such as architecture, construction engineering, informatics, mechanical engineering, automation, and ICT. Unfortunately, this type of multidisciplinary professional is scarce, a consequence of the conventional education curriculum.

Despite the challenges, the CIC project demonstrates a systematic approach that methodically addresses the aforementioned issues. These tasks would have been extremely difficult to achieve without the support from the CIC and the local construction practitioners.

There is one aspect that could have been done differently that may have resulted in better outcomes. As mentioned earlier, the project was wholly financed by the CIC and the initial objective of the project was to investigate the potential to implement automation and robotics in the context of the Hong Kong PHC. The CIC was insistent that if the project produced positive outcomes in the first phase, they would continue to finance the remaining phases of the project even though the costs of the second phase of the project are significantly higher than those of the first phase. Because of these unknown high costs, the CIC has put the second project phase on hold and hopes that industry partners will share the costs and risks in the future (see explanation in chapter 4). In the future, it would be better to have a clear project goal at the beginning and to involve the industry partners, specifically as potential investors, in the early stages of the project. Even though the industry partners were involved in the surveys, the on-site case studies, and the co-creation workshops, they only played a supportive role, not the role of a potential user or investor. For this reason, they did not continue to participate in OCR development and are now not fully aware of the benefits, design objectives, and performance of it. Even though the proposed OCR can be used in any PHC site in Hong Kong once it is finalized, for now, the demonstration mock-up is only for stimulating awareness of OCR in the construction industry. The mock-up is not tailor-made for any specific contractor in Hong Kong making the contractors hesitant in financing the remaining project. Involving the industry partners in the early stages as potential investors will make them more likely to participate in the project proactively. This would also allow the product to be tailor-made to their specific requirements, business model, and budgets. Therefore, a transparent project direction and sufficient financing would allow the development team to follow a well-defined project roadmap to push the OCR closer to market uptake.

The ROD concept is the essence of implementing automation robotics in the construction industry and emphasizes the idea that when implementing construction robots, all construction design parameters should be designed to ease robot operation either on- or off-site and all building components should be designed for a robot to easily grab, transport, and position (Bock, 1988). As Figure 104 illustrates, the left side of the existing façade type used in the Hong Kong PHC sector has protruding parts with uneven surfaces. The complex design presents many challenges during the OCR development because the OCR would need at least five DOF plus additional sensors to ensure the end effector could cover the most surfaces. As a result, an OCR design for the existing façade would be more complicated and costly. In addition, even though the proposed OCR can adjust to façade geometry, it would still be hard to verify whether the system performance is better than a human, in items of speed, quality, and cost-saving. Contrastingly, the façade on the right has taken the ROD concept into consideration: the design has been simplified and the protruding parts have been eliminated. This design change can directly influence the OCR design, including reducing the DOG from five to three, requiring fewer sensors, and consequently significantly reducing the cost of the OCR. Furthermore, the simple geometry allows the OCR to embody greater reliability and performance than its human counterpart. Unfortunately, it has proven challenging to promote the ROD concept to the construction industry. During the co-creation workshop, the TUM team enquired about the possibility of altering or simplify the existing façade design, but the answers from the participants were contradictory because any changes made on the façade panel would potentially change the entire existing supply chain and regulatory terms. As known, the construction industry is reluctant to change the existing design, working methods, or institutional aspects and therefore adopting the ROB concept seems too radical for the industry to accept. It is for this reason that Prof. Thomas Bock made a ten-year long-term plan for the Hong Kong construction industry and aims to guide the industry to transform incrementally. In addition, depending on their size, resources, and business strategy, some companies can adapt to changes better and some can make changes faster than others. Two scenarios and examples are presented to investigate how to promote the ROD concept with respect to larger organizations.

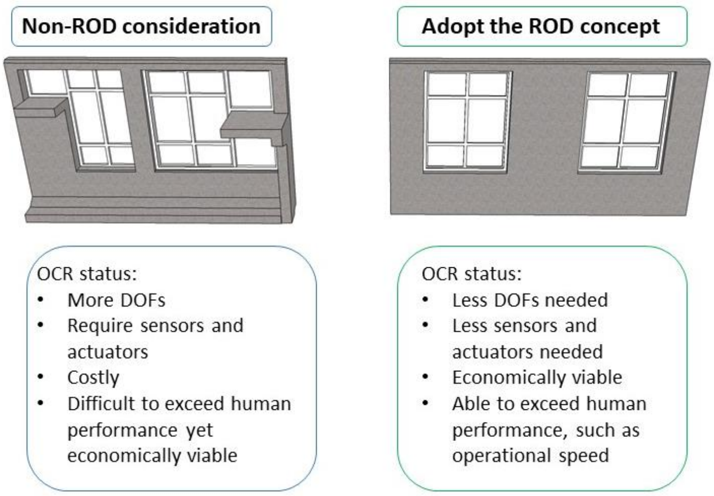


Figure 104: ROD concept in building element design.

The first scenario is premised on the theory that larger organizations will be working together to develop OCRs, see Figure 105. The major driver for such cross-industry collaboration is when the construction industry is suffering from an urgent situation and desperately needs to upgrade and the involved partners must be willing to accept changes and compromises. This is often a lengthy process as government authorities will play an important role in providing incentives that promote the R&D efforts as well as amending existing regulations that obstruct the implementation of automation and robotics in the construction process. Because of the various backgrounds of the involved project partners, it is crucial that the final solution based on the ROD concept will bring mutual benefits to the involved parties and satisfies each partners' demands and interests. However, the primary end-users of the solution are those construction-related partners that directly benefit from the developed solution. In contrast, the technology providers, such as robotic specialists, technical consultants, and system integrators will only benefit after the developed solution reaches an economy of scale, otherwise, it is only a project-based service, which would open a new market for the partners. The characteristics of this scenario are its focus on an industry-wide transformation, the high R&D spending, and the long development duration. Overall though, the ultimate positive influence on the construction automation will be compelling.

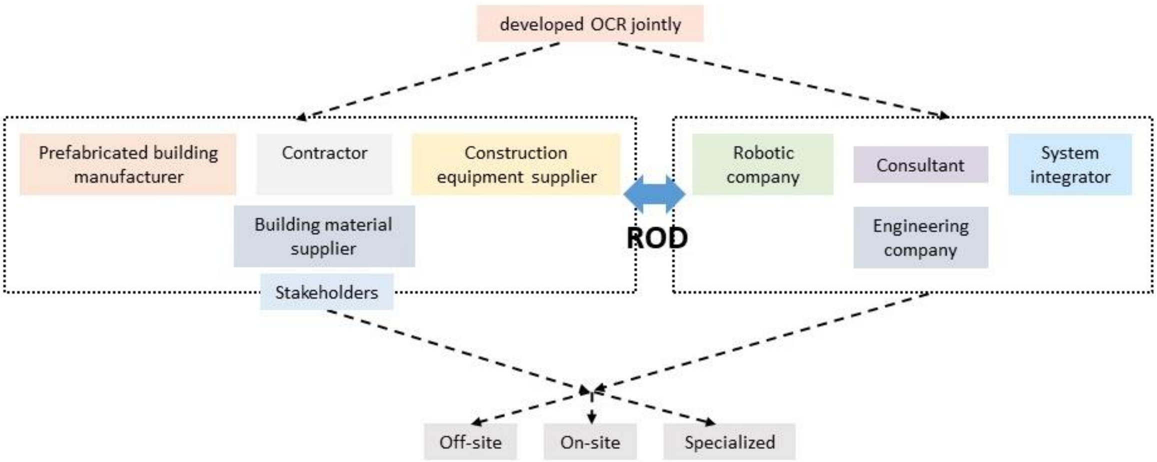


Figure 105: How large companies adopt the ROD concept.

During the late 1980s, the Japanese construction industry started to experiment with automation in the entire construction process with aims to improve on-site safety and efficiency and to minimize manual activities. In this period, many major construction companies engaged in the development of automated construction systems, such as Shimizu, Obayashi, and Kajima. Most of the developments were based on a similar method as the first scenario described above. The Automated Building Construction System (ABCS) will serve as a relevant example. The ABCS was initiated by Obayashi in 1993 and jointly developed by organizations from various specialities. The building components were designed to ease on-site assembly by the material lifts and crane system and, in addition, the prefabricated façade system was equipped with a custom interlocking system to facilitate final positioning and assembly (Ikeda and Harada, 2006). Overall, on most ABCS sites, the on-site automated construction site and the building components were complementary to each other to enhance overall construction performance making this one of the best examples to demonstrate how ROD is adopted in cross-industry collaboration.

The second scenario is based on the SME-oriented approach that focuses on the company's specific requirements, primary target market, and desires for a joint venture partnership, see Figure 106. The motivation for the SME is the opportunity to open up a new market besides the competitive existing market. Due to smaller numbers of involved partners, the requirements, project scopes, and expected outcomes can be identified quickly with a specific focus. The optimal goal is to develop a marketable solution that makes the company stands out from the competition but not isolated from the existing market. Therefore, more R&D efforts will be concentrated on how to develop a product that is attractive yet compatible with the existing market, rather than something that is radically different from the existing market. The characteristics of the SME-focused scenario are its focus on the short-term objectives of the involved parties and the shorter initial R&D duration with an explicit strategy of how to adopt the ROD concept. This type of collaboration would not trigger a radical industry-wide transformation but the involved organizations would adhere to incremental changes.

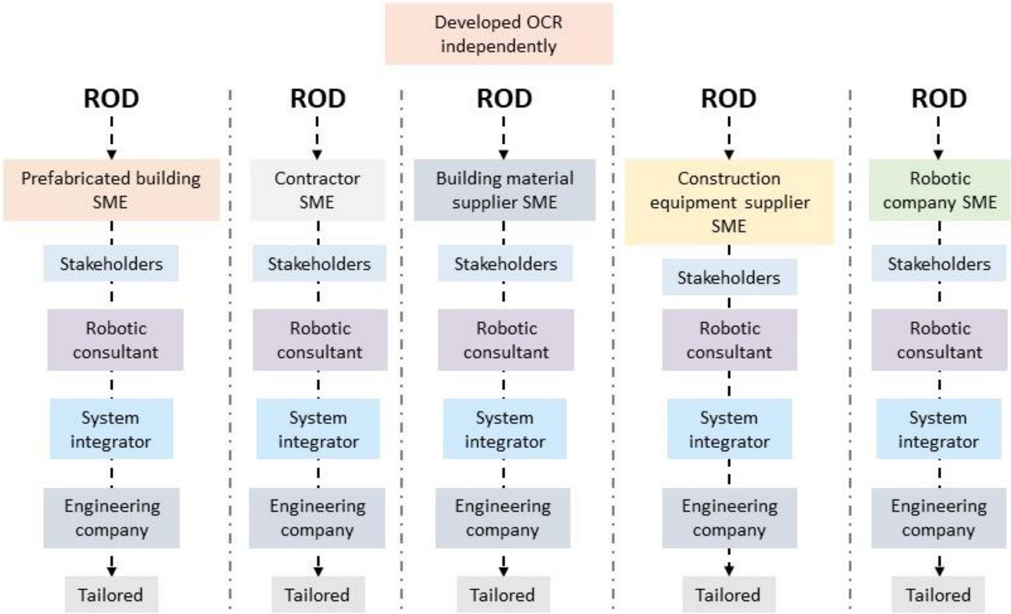


Figure 106: How SMEs adopt the ROD concept.

The bricklaying robot called HadrianX, developed by Fastbrick, provides an interesting case for demonstrating how a SMEs has adopted the ROD concept and was reinforced by a joint venture partnership. HadrianX is an advanced bricklaying OCR and the system is based on an expansive crane-like system equipped with a customized end effector that is able to grip and position bricks with astonishing speed and precision. The company has incorporated a joint venture with a building product company called Brickworks. Brickworks has started developing an optimised brick system that is suitable for use with the HadrianX system. This is a typical manifestation of the industry utilizing a ROD concept to develop their own OCR product. The terms of the joint venture give exclusive rights for Brickworks to provide the bricks to Fastbrick and they continually improve the brick design for HadrianX. And because Fastbrick has been granted the exclusive rights to provide bricklaying services to Brickworks, the collaboration brings mutual benefits for both parties as well as helped bring HadrianX from being a prototype to a fully commercialized product (FBR, 2019).

6.3 Summary

This chapter presented a generic roadmap that offered an overview of the tasks, milestones, goals, and time frames of carrying out OCR development. The roadmap was developed with a focus on how to bring OCR from the research stage to near-mark uptake stage. Furthermore, the roadmap provides basic information that is essential for formulating the design guidelines. The guidelines have the OCR development divided into eleven stages and concentrate on the initial research stage to the dissemination and exploitation stage. The categorized sub-tasks in each project stage are emphasized along with their corresponding objectives. Alongside the guidelines, recommendations were given and particular attention was paid on the first four OCR development stages. A practical method, known as NPV, was introduced and can assist the prospective decision-maker in carrying out a CBA while the OCR is still under development. The attributes that can potentially prevent or slow down OCR implementation were also presented. When conducting such a project in the future, special consideration needs to be taken in regard to how to overcome those identified attributes proactively.

Next, the lessons learned based on the experiences gained from the CIC project were summarised before two scenarios were illustrated to demonstrate how the ROD concept can be implemented in practice by different sizes of organizations and with different types of collaboration. Overall, the roadmap, guidelines, and recommendations presented in this chapter can be used as one of the objective decision-making tools for OCR development. Knowing how to interpret, absorb, and utilize the knowledge is entirely dependent on the individual circumstance of the organization that would be willing to conduct a similar project.

7 Conclusion and future work

The consultancy project on the Potential of Implementing Robotics and Automation in the Context of Large-scale Housing Development for Hong Kong was commissioned by the CIC. This dissertation documented the first phase of the project, each progression thereafter, evolutions, and outcomes were presented. As a result, a multifunctional façade finishing robot was proposed and designed and a mock-up was demonstrated. Encouragingly, the consultant project was successful and the outcomes exceeded the client's expectation. The CIC project not only provided a great opportunity to evaluate the possibility of implementing automation and robotics technology in the Hong Kong PHC sector but also elicited valuable information for developing a methodological approach that can be used as a decision-making tool to encourage the construction industry to initiate similar projects in the future.

Chapter 1 presented the background information of the research and verified the reasons as to why implementing automation and robotics is such a challenging task as well as illustrated the research gaps, objectives, questions, scopes, and methods. Chapter 2 identified the challenges faced by the Hong Kong construction industry, particularly by the PHC sector. State-of-the-art OCR technologies were introduced and the obstacles and concerns that the conventional construction industry needs to take into account when adopting OCR were evaluated. Chapter 3 provided the main content of the dissertation and demonstrated the comprehensive methodological approach on how to conduct OCR related projects using the CIC consultancy project as a case study. Chapter 4 focused on a potential business strategy development based on the proposed OCR and described the market analysis, market positioning identification, customer segmentation, and value proposition. A potential business plan was also recommended based on the research and CBA outcomes. Chapter 5 presented a method of how to estimate and formulate system performance indicators when the system is still under development and proposed how to continue the remaining tasks and push the OCR closer to market launch. In addition, the critical risks regarding OCR implementation were evaluated. Chapter 6 focused on providing a roadmap and guidelines to facilitate the decision-making process when carrying out OCR development. Based on the CIC project, the lessons learned provided an informative indication of how to address issues in the future.

7.1 Answers to the research questions

This section outlines the key findings and contributions of the dissertation with respect to how to address the research questions raised in chapter 1.

1. What types of challenges are the Hong Kong construction industry, especially the PHC sector, facing?

   In section 2.2, an overview of the Hong Kong construction sector was introduced. Despite the increasing output values of the construction industry, the Hong Kong construction industry still faces many challenges (a detailed description was featured in section 2.4). The primary constraints include consistent cost escalation, land shortages, labour and skill shortages, and health and safety-related issues. Many of the challenges of the Hong Kong PHC sector are shared by housing sectors elsewhere while some are more distinctive to the HK PHC sector, such as increasing demands on public housing (as discussed in section 2.3.1). According to government projections, the Hong Kong PHC sector is scheduled to construct approximately 460,000 units in the next decade (Hong Kong Housing Authority, 2018). Recent efforts on prefabrication and off-site construction techniques typically only benefit larger organizations, not local SMEs, and there are few incentives offered by the government to encourage the Hong Kong PHC sector to adopt new technologies. The Hong Kong PHC sector is fully aware of these issues and requires urgent aid from the government and construction experts and practitioners in solving these aforementioned challenges.

2. What are the characteristics already possessed by the Hong Kong construction sector that will support OCR implementation?

   Successfully implementing OCR technology requires a number of factors and it is, therefore, important to verify whether the Hong Kong construction sector has what it takes to transform from a conventional sector to a sector that is driven by I&T. Sections 2.2 and 2.3 evaluated the current situation in the Hong Kong construction sector and identified the challenges faced by the industry. The evaluation results have indicated that the Hong Kong construction industry faces a set of unique challenges, but industry practitioners are attempting to search for alternative solutions. Apart from a willingness to transform, the author identified the following factors that suggest the Hong Kong construction industry has sufficient resources to carry out OCR implementation. The detailed analysis of this was demonstrated in sections 2.4.2 and 4.1.

   - Economical: Hong Kong retains a fast-growing economy that benefits from its economic freedom, low tax rates, high-quality infrastructure, and institutional quality (Chiu, Ho and Lui, 2018).
   - Geographical: Hong Kong is situated in a well-connected strategic location that allows Hong Kong businesses to retain close relationships with mainland China as well as to act as a gateway to the rest of the world. The location facilitates the openness of the markets and enables the Hong Kong industry to receive the most up-to-date information.
   - Technological: Even though the construction industry in Hong Kong experiences a variety of challenges, the industry is in the forefront position in terms of super high-rise building construction, high-density urban planning, and construction management. The Hong Kong construction industry has spent a huge amount of resources on implementing prefabrication, BIM, and modular construction technologies. In addition, the HKUST, CIC, and HKSTP have initiated collaborations and R&D schemes that focus on how to implement automation and robotics applications in specific construction tasks.
   - Organisational: The CIC provides support and communication channels between the construction industry and the government and aims to improve the overall performance of the construction industry. The HKSAR considers I&T

development as the key to maintaining sustainable economic growth and the government has played an important role in promoting home-grown knowledge-based business sectors. Section 4.1 illustrated a number of incentives and funding schemes provided by ITB, the Development Bureau of Hong Kong, the CIC, and private investments. The construction industry will benefit from long-term commitments and resources distributed to support industrywide I&T efforts.

3. How can existing on-site construction tasks potentially be optimised by adopting construction automation and robotic technologies?

   This was one of the most common questions raised by the construction practitioners during the course of the CIC project, but there is no straightforward answer to the question. The answers depend on various attributes from the construction industry. In general, the construction industry is a complex and dynamic industrial sector in which the working environment, logistics, skill sets, and information are fundamentally different from other industry sectors, such as the manufacturing industry.
   To answer the question, the following methods were developed:

   - The first step is to conduct the initial research by working closely with construction industry practitioners. During this stage, the design team can predominantly use the data gathered upon the previous experiences and research outcomes to support the decision-making process. There are three objectives, including being familiar with the construction tasks by understanding the working methods, tools, and information transfer methods applied; introducing the proposed technologies – referred to as automation and robotics technologies – to the selected stakeholders; identifying the characteristics of the construction tasks, such as identifying the challenges and weaknesses imposed by labour. Sections 2.5.2 and 2.5.3 provided insights on why and how to automate manual tasks and conducted a comparison between the manufacturing and construction industries. Section 2.5.3 exposed the potential challenges of when to adopt automation and robotics technology in the construction industry.

   - Based on the networks established during the initial research phase, define the appropriate stakeholders for surveys and interviews. These communications can be carried out based on a hierarchical order. For example, construction practitioners from higher management levels tend to judge the proposed technology based on operational performance, safety, costs, and regulatory requirement aspects. In the early development stages, without pilot testing and previous experience, there is a lack of tangible data that can be used to measure these attributes. Consequently, the comments from the higher management levels during this stage will reflect the general opinions of how the construction industry perceives automation and robotics technologies. The online survey is, therefore, the optimal channel to engage stakeholders from a higher status within an organization. In contrast, the frontline workers, contractors, and project management teams will provide comments that are more based on the daily operation of a specific construction task, which provides essential details about the methods, tools, and issues that occur during an on-site task. The information collected from the lower hierarchical levels is highly valuable for the design team for deciding which on-site construction tasks need urgent improvement. The optimal method for engaging with the lower hierarchical groups is through on-site visits and face-to-face interviews. Section 3.3 described the online survey method used in the CIC project and the detailed descriptions of the on-site case study are featured in section 3.4.

- Followed by the surveys and interviews, if the design team has sufficient financial means and is not under strict deadlines, it is highly beneficial to organize co-creation workshops. The co-creation workshops encourage stakeholders from a wide range of disciplines and focus on two groups of participants: one from the management level and the other from the highest decision-making level. A co-creation workshop is divided into two topics: a technical session – system selection, technical applicability, compatibility with the existing construction methods – and a policy session – institutional topics and business strategies. A co-creation workshop is an effective tool to narrow down the research areas and to prioritize the research direction. Ultimately, it offers insights into which system should be developed and how the industry can prepare and adjust to changes that are attributable to the proposed technology. Section 3.5 described the method used to conduct the co-creation workshops in the CIC project.

- After gaining insights from the construction practitioners, at this stage, the design team should be clear about which tasks require improvements. This step is to establish what drives the industry to upgrade and to verify whether automation and robotics technologies offer the most appropriate solution, and if not, what the alternative approaches are.

- If automation and robotics appear to be the most applicable approach, the design team has to conduct an initial market analysis to identify which off-the-shelf products can be used without extensive modification, which assists the project team in estimating the resources demanded by the proposed development. For example, the development time and cost can be reduced significantly if the proposed product can use off-the-shelf products. In addition, investigating whether the existing infrastructures support the proposed technology and considering optimization solutions if the existing infrastructures are not compatible is crucial.

4. How can keys stakeholders and their requirements in the context of OCR development be identified?
   The Construction industry possesses a wide range of stakeholders and each one may have different roles and interests that could influence each step of the construction task.

Section 2.6 evaluated the challenges faced by the construction industry when attempting to maintain excellent communication, achieving mutual understanding, forming alliances, and mitigating conflicts of interest between various stakeholders. Undoubtedly more stakeholders will be involved in the decision-making, design, marketing, and management processes when introducing OCR to the construction industry so it is vital to identify the stakeholders, their interests, conflicts, roles, and responsibilities in an early stage. Based on the CIC project, the practical methods to tackle this task happens in five sequential steps (the detailed descriptions are demonstrated in section 3.2).

- The first step is the classification of the stakeholders based on their needs, interests, and industry sectors. For example, the main industry sectors consist of public, private, and societal. It is then necessary to divide the defined sectors into two groups, primary and secondary, then into two classes, voluntary and involuntary, and finally, into two elements, internal and external.

- The second step is to disaggregate stakeholders according to their unique interests, demands, and potential impacts on the proposed activities.

- The third step is understanding the disposition of the stakeholders and evaluating the power transformation of stakeholders across different phases of the project. The "Power-interest Grid" was adopted in the CIC project to analyse the power shift and it can be used as a guideline.

- The fourth step is to evaluate the interests of each stakeholder in different project phases, respectively. The outcomes can be used for prioritizing stakeholders and positioning them in a hierarchical order.

- The fifth step is understanding the engineering requirements, which ensures accurate decision-making, focused development strategies and keeps a smooth overall development process. The engineering requirements process can be divided into five tasks, including the initial requirement identification, functional and non-functional requirements categorization, requirements prioritization, specification identification, and requirements validation.

5. How can the optimum allocation of functions between man and machine, Degree of Freedom (DOF), sensory technologies, hardware, software application and Degree of Automation (DOA) when developing OCR be identified?

   This question is closely related to question three above and those answers offer preliminary insights for this question. Frankly, if a human can carry out a task faster and cheaper than a machine or robot then there is no immediate need to adopt automation unless the working conditions are highly risky. However, conjecturally, allocating humans and robots appropriately require a thorough investigation and a systematic approach. The designer needs to verify why the specific task needs to be automated and then study human and machine capabilities to evaluate whether the decisions made can embrace human-machine strengths as well as mitigate weaknesses through a complementary approach. Section 2.5.2 provided an in-depth analysis of how to determine the allocation of functions between humans and machines. In section 3.6.1, a systematic approach was developed based on the Price-Tabachnik Descriptive Procedural Model and the CIC project as a case study. The approach divides the function allocation process into eight stages (Price and Tabachnick, 1968).

- The first step is to conduct task identification that assists the design team to understand the sequence, tools required, skill sets, motions, and managerial qualities associated with the task.
- The second step is to evaluate tasks to determine if it must be automated.
- The third step is to define whether or not OCR can carry out the task, or whether assigning the work to human is necessary.
- The fourth step is to investigate whether human involvement is feasible.
- The fifth step is to verify the hypothesized man-rated functions.
- The sixth step is to study human functions and provide solutions other than automation.
- The seventh step is system engineering.
- The eighth step is to determine whether automation is achievable for the specific task.

The eight steps above assist the design team in deciding which parts of the task need to be automated and the outcome provides insights that can be used to define the initial DOF of the proposed system. Determining the optimum levels of automation for the proposed system require a sequential set of processes. During the construction task, the design team needs to understand how information is being collected and analysed, how decisions are being made, and how the decisions are being implemented. These analyses need to be conducted based on the attributes from both manual and automated methods. Four human performance categories need to be taken into consideration when determining how automation will influence human performance, including mental workload, situation awareness, complacency, and skill degradation. Based on that analysis, the design team will be able to answer the following questions: What should be automated? Why type of automation should exist? What is the optimal level of DOA? These exercises can help the design team with decision-making while developing the program architecture, control method, and system integration strategies for the proposed OCR.

6. How can OCR technologies be introduced to the conventional construction industry?

Introducing innovative technologies such as OCR into the construction industry involves many stakeholders and organizations that are committed to a new way of thinking. OCR innovation requires involvement from all stakeholders in a cross-disciplinary approach through collaborative industry relationships and encouraging regulations, incentives, and innovative procurement systems (Arditi, 1983). In practice, expecting the same level of enthusiasm from all stakeholders is a challenge. The main difficulties associated with introducing innovation in the construction industry were evaluated in sections 2.6 and 6.2.3 and the key challenges are listed as follows.

- Fragmentation of the construction industry: The construction industry has a very complex structure that involves a multitude of stakeholders. Each stakeholder has a specific area of interest and expertise governed by different institutional (Winch, 1998) market awareness: When key stakeholders, especially construction practitioners, regulators, and investors, are not familiar with the proposed technologies, the OCR can be seen as a radically new technology that only contributes to a niche market. However, very few OCR products have been commercialized or can be used as a comparable reference that helps key stakeholders relate OCR to their professional domains. Examples of commercialized OCRs are featured in section 2.5.5. Ultimately, unfamiliarity with the technology can reduce commitments from the industry as well as confidence from potential investors.

- Reluctant to radical changes: The construction industry is supported by well-established infrastructure, supply chains, regulatory systems, professional services, procurement systems, and legal protection systems. Any radical changes may have significant implications for the existing operations and affect involved parties' stakes and resistance to change only increases negative attitudes towards OCR adoption.

- Lack of cross-disciplinary collaboration: The construction industry has been described as highly fragmented and lacking in partnership and collaboration between supply chains (Abadi, 2005). In practice, the collaboration between architects, structural engineers, quantity surveyors, local authorities, contractors, and the client is rigid, but in terms of academics, there is a lack of effort for interdisciplinary teaching and learning.

The methods for introducing OCR technologies to the conventional construction industry often use a short-term or medium-to-long-term strategy as demonstrated in section 6.2.3. In general, as part of the short-term strategy, the development team needs to increase industry awareness of OCR technologies by producing promotional materials such as brochures or booklets, inviting key stakeholders for brainstorming sections and workshops, and organizing tours that focus on disseminating the state of the art technologies in the relevant industry fields. When developing the OCR system, in order to gain acceptance from the industry, the system needs to be compatible with the existing market structure to avoid radical changes. The short-term goal is to stimulate the industry with a simple, reliable, and cost-effective system. If this is accomplished, the industry will gain experience, confidence will increase regarding OCR, and technology will increase incrementally. Alternatively, the medium-to-long term strategy focuses on industry-wide transformations. Here, the government plays a key role in coordinating cross-disciplinary collaboration, providing incentives for R&D efforts, and contributing policies and regulations that support OCR adoption. The researchers and designers need to ensure that the proposed system will bring mutual benefits to the involved parties and satisfies each partner's demands and interests. Because the construction industry has experienced unbalanced challenges, capacities, demographic issues, and institutional systems globally, deciding which one is the most suitable strategy solely depends on the individual circumstances of the specific construction industry.

7. Which type of KPIs associated with OCR should be verified during the system development stage?

   The characteristics of construction tasks, such as working environments, operator skillsets, system specifications, and the requirements of the job, are fundamentally different between industrial robots and OCR, but defining KPIs during the early stages of the development is crucial for decision-making, product planning, improvement, and iteration strategies (Echelmeyer *et al.*, 2011). Section 5.1 provided a detailed analysis of which are the relevant parameters to measure OCR KPIs. In general, the relevant parameters consist of four major categories.

   - Task-based parameters: These parameters are used to measure how the OCR specifications match the operational requirements from the aspects of the job site compatibility, flexibility, motion, accuracy, and reliability.

   - Safety-based parameters: These parameters focus on measuring pHRI-related subjects, such as the assigned torque and operational speed and are under the safety requirements of a construction site. Safety protection measures are also taken into consideration during the system design phase.

   - Design parameters: These parameters are used to measure the hardware and software flexibility of the system and economic feasibility and to address soft factors that encourage the construction industry to accept OCR incrementally.

   - Efficiency parameters: These parameters are used to determine the factors that influence operational efficiency. Which factors lead to downtime or long setup times? What kind of impact could be caused by complex engineering and a lack of adequate skill sets?

The identified parameters assist the design team in determining the initial KPIs. It is crucial to establish them in an early stage so that the KPIs can be verified as the development proceeds.

8. What is the appropriate business model for the proposed OCR?

Chapter 4 investigated this question based on the CIC project. A number of methods were described concerning market positioning analysis, customer segmentation, and value proposition analysis. The potential business model was based on the results from the target market investigation, which indicated that it is better to adopt the Rent Instead of Buy business model as well as to offer comprehensive services. Many tasks are required during market uptake, especially when dealing with radically new technology trying to enter a niche market. Only large companies can facilitate extensive workloads, such as providing exclusive aftersales support and organizing training programs for the customer. Therefore, the Rent Instead of Buy business model is suitable for SMEs or potential spin-off companies so that the additional tasks other than delivering services can also be carried out in-house.

9. How can the value of the OCR be measured in an early stage of the project?

Although it is fairly straightforward to quantify the benefits of using OCR when the data regarding the comparison of costs, specifications, and performance between manual methods and automated methods are available, in the case of OCR, there are very few examples of a commercialized system available for the investor to use as a reference. To continue developing OCR from a conceptual idea to a fully functional system requires sufficient funding so it is vital to convince investors to support OCR in an early project stage. There were two methods used in the CIC project to estimate the value of the proposed OCR. The first was the CEA method and focuses on measuring non-monetary outcomes, such as conducting incremental cost and benefits analysis (Svensson and Hultkrantz, 2017). The second was a CBA that focused on costs and benefits associated with monetary terms. In the CIC project, the NPV costs and benefits method was used (Warszawski, 1985). The data collected from the previous investigations, such as the initial research, stakeholder analyses, on-site case studies, co-creation workshops, initial designs, dissemination, and market analyses, can provide valuable information for carrying out CEA and CBA. Furthermore, the data can help the design team achieve accurate results before the OCR is tested and finalized. Section 4.4 described the CEA and CBA methods used in the CIC project.

10. What is the purpose of the guidelines and how will they be used?

The construction industry functions differently from other sectors, such as automotive and manufacturing. Automation and robotics technology are one of the many solutions for improving the overall performance of the construction industry (Li, 2018). Notably, automation and robotics technologies are more mature in other industry sectors compared to the construction industry making introducing technology into the conservative construction industry can be very challenging.

The guidelines were developed based on the CIC project and provide a comprehensive tool to facilitate the decision-making process from the initial research stage to the mock-up building stage. The rest of the project stages were explained briefly and section 6.2

described the guidelines. In one way, the entire dissertation can be considered as a guideline that offers an extensive explanation of how to evaluate challenges, demands, and requirements from the Hong Kong PHC sector. The methods of transferring the concept to a practical OCR product were developed and the techniques and recommendations of how to bring the proposed OCR to near market uptake phase were demonstrated. Although the context of the study concentrates on the Hong Kong PHC sector, the methodology developed could be considered as a universal approach to assists the construction industry as a whole in executing a similar type of project in the future. The key stakeholders need to be aware of the circumstances of the market demands, strengths, and weaknesses of the local construction industry so it is highly effective if the key stakeholders have a satisfactory level of knowledge of either construction or robotics, but always have the option of referring back to the guidelines for assistance.

7.2 Recommendation for future work

Bringing the proposed OCR from the current stage to the near market uptake stage is an incremental process. This section evaluates the current market readiness levels of the proposed OCR, projecting the remaining tasks for future development. The dissertation presented three PoC technologies: the stabilization system, the object segmentation via Deep Learning, and the PIM. The current concepts, functions, and the development stage are featured in section 3.7. The above technologies represent the innovativeness of the proposed OCR and determine the unique selling points of the product, but all of those that are under the PoC stage will take time and extensive tests to develop them into a practical application. The following section will briefly describe further technical developments required of the PoC technologies.

- Future work for the proposed stabilization system:

  The proposed localization system consists of three subsystems: (a) the detection system, (b) the stabilization system, and (c) the final positioning system. Future work will be extended in these three directions.

  For the detection system, the type of sensor matters for the task and consequently determines the control method of the stabilization system and the final positioning system. For example, a laser sensor may be sensitive to dust particles or reflective surfaces such as glazing and metal, but on the other hand, a gyroscope sensor may require high precision of the reference façade. Thus, it is critical to select the appropriate sensor for dedicated working environments.

  For the stabilization system, the ability to perceives the current pattern of the system sloshing is highly required. To stabilize quickly, the system should adopt active and passive compliant control methods to eliminate the external influence (i.e. the wind, an unexpected collision). In section 3.7.1, the impedance control law was described.

For the final positioning system, because it should be able to guide the end-effector precisely to the target position, an efficient and robust position controller should be implemented.

It is crucial to test the localization system before the final pilot runs to reduce the risk of system failure, damage, or safety hazards. To test the effectiveness of the localization system, it is necessary to build a fully functional simulation or prototype that can be used for laboratory testing as well as pilot testing. ROS and Gazebo will be used to create a simulation environment. First, the robot model is imported into the scene; the joints and links should be claimed and the joints should be connected to the controllers. Then, the sensors are attached to the robot and configured. Finally, an experiment with the model and sensor will be created to test the localization system.

- Future work for the proposed object segmentation system:

An object segmentation via the Deep Learning method was introduced in section 3.7.2. The Neural Network Model was established to train the segmentation process and the results have proven that the proposed approach is viable. It is important to note that the images for the data training were taken from the ground level, but in the real case scenario, an on-board camera that is close to the PCF will capture the dataset image. The ultimate goal is for the system to automatically detect the windows or other types of openings for any style of building in real-time. The segmentation analysis will facilitate the OCR in determining the painting ranges and accelerating over the areas where the windows or openings are positioned to achieve maximum efficiency and to achieves this goal, the following developments are necessary.

Based on the proposed method, inputting more close-up images into the system will ensure that the algorithm can distinguish the differences between wall surfaces, window frames, and openings. One viable method is to use coloured strips to cover the edges of the window frame. In principle, the system would be trained to identify the colour changes between the wall and the colour stripes in that that the coloured strip means "not a window" and the end effector would then accelerate until the next coloured image is detected. To implement this approach, extensive system training is required. A scale mock-up of the on-board camera needs to be constructed to test camera performance, image capture methods, and integration methods and to optimize the control method.

Furthermore, in image processing machine learning methods, a general rule of thumb is that the more 'training image data' available, which is similar to predictions, the better the accuracy will be in those predictions. Therefore, by using close-up images of the window and coloured stripe edges, the existing Neural Network Model can be augmented using the current pre-trained model, which was trained on the full-scale images. In principle, this approach can help the neural network correctly recognize the realistic window border scenario.

- Future work for the proposed PIM concept:

An overview of the PIM concept was introduced in section 3.7.3. The objective of the PIM concept is to incorporate OCR into the conventional construction management process that facilitates real-time data collection, processing, and distribution while using OCR, thus enhancing the overall decision-making during a specific construction task.

The PIM concept was evaluated under the general IFC architecture to demonstrate how PIM applications would operate while using the standard BIM data in a case study. During the PoC research, the task breakdown, property setting, and automated data assignment were tested, which enabled accurate data flow under the data input trials. However, the proposed approach is still unable to collect, process, and manage real-time data that has been generated by the OCR due to the proposed OCR still being under development.

In terms of future development, a comprehensive research project is needed to develop the hardware and software environment. First, the fully functional prototype of the proposed OCR needs to be completed. The second task is then to build a scenario within the entire painting task that comprises manageable levels of data. For instance, using the painting task as a scenario and then analysing how the OCR collects the data, analysing the method of processing information within the PIM system, defining the appropriate user interface, and understanding how to transfer the data to the most desired stakeholder. To accomplish these tasks, a close collaboration between Date Engineers, robotic designers, programmers, and construction managers are essential (Pan, Ilhan and Bock, 2018).

In section 2.6.3, the different categories of market readiness levels were explained. The estimated market readiness levels of the proposed OCR are shown in Table 55. Because the proposed OCR is still in an early development stage, the PRL and Institutional and legal readiness levels will not be projected under the current situation.

Table 55: Estimated technology readiness levels.

Estimated Technology Readiness Levels					
TRL6	System/subsystem model or prototype demonstration in a relevant environment (Mankins, 1995)				
Estimated integration Readiness Levels					
IRL 3	There is compatibility (i.e. common language) between technologies to orderly and efficiently integrate and interact (Sauser *et al.*, 2006)				
Estimated system Readiness Levels					
SRL 3	Develop a system of incremental capability; reduce integration and manufacturing risk; ensure operational supportability; reduce logistics footprint; implement human systems integration; design for producibility; ensure affordability and protection of critical program information; and demonstrate system integration, interoperability, safety, and utility (Sauser *et al.*, 2006)				
Estimated innovation Readiness Levels (IRL)					
IRL 4	Technology	Market	Organization	Partnership	Risk
(Lee, To Chang and Chang	General availability to the market; establish after-	The business model established;	Inter-organizational innovation; cooperation	Cooperation with dynamic network	Organizational risk periodically assessed

Chien, 2011)	sales supports; design and facilitate continuous innovation	competitors identified	inside the value chain		
Estimated demand Readiness Levels					
DRL 3	Identification of the expected functionalities for the new Product/Service (Paun, 2011)				
Estimated manufacturing Readiness Levels					
MRL 4	Capability to produce the technology in a laboratory environment (OSD Manufacturing Technology Program, 2010)				

The various market readiness levels indicate that the proposed OCR has reached relatively high TRL, but the design has not yet been tested in a laboratory or on-site environment. Therefore, functionality or practicality related readiness levels are still low. As mentioned in section 3.1, the entire project was divided into four phases and the phase two project focused on detailed design and pilot testing, which will both increase TRL, IRL, and SRL significantly. Phase three and four will focus on improving the Innovation Readiness Levels, DRL, MRL, PRL, and Institutional and legal readiness levels. The completion of phase two of the project will determine whether the proposed OCR can be commercialized. The remaining phases of the project are illustrated in Figure 107. The patent is currently under application and although local contractors and investors have expressed their interest in further supporting the project, due to institutional reasons, the follow-up project is currently on hold.

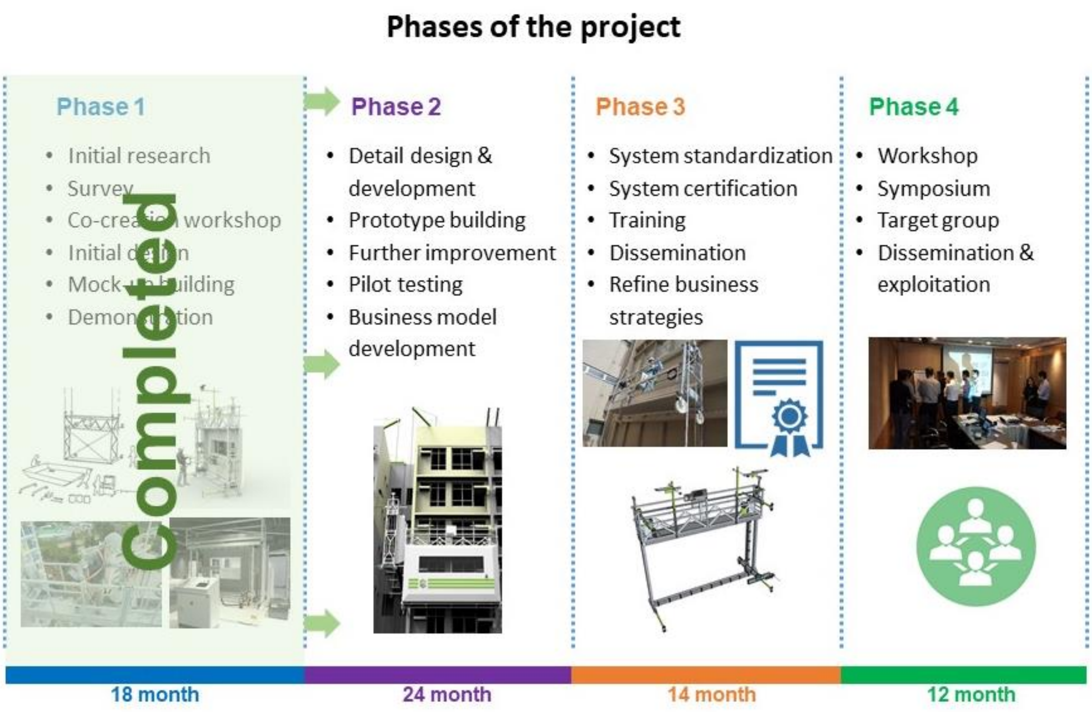


Figure 107: Different phases of the CIC project.

7.3 Conclusion of the proposed methodological approach

This dissertation presented a comprehensive methodological development process for exploring the potential to implement automation and robotic technology in the context of the PHC sector in Hong Kong. The CIC has provided a unique opportunity to channel connections between the construction industry and the academic research communities. The aim of the project was to identify the challenges faced by the construction industry and to seek answers from cross-industry technologies in order to enhance the overall performance. The CIC project has demonstrated two characteristics of research that have evolved from basic research into applied research over the project duration. Subsequently, the proposed methodological approach revealed the processes while carrying out both types of research activities. During the CIC project, there were various methods developed within each project stage. The focus was placed on the first project phase that covered from the initial research stage to the mock-up building stage, but the rest of the project stages were briefly mentioned.

By following the proposed methodological approach, the current situation of the Hong Kong construction industry, in particular, the PHC sector, was thoroughly investigated. The key stakeholders and their requirements were identified through surveys, interviews, on-site case studies, and co-creation workshops. These methods have generated rigorous outcomes that assist the project team in deciding the priority research areas and in determining that the on-site façade painting task has the highest potential to apply automation and robotics technology. During the initial design stage, a range of systematic decision-making tools was developed to determine the optimal DOFs and levels of automation for the proposed OCR. By working closely with construction practitioners, three PoC technologies were developed that aimed to provide a feasible and practical solution. In general, supported by a CBA and suggested business strategy, the proposed OCR has demonstrated considerable potential in practicality, efficiency, and market applicability. The mock-up is currently displayed in CITAC and has generated positive comments and inquiries from the exhibition visitors. This is a significant step for the PHC sector in Hong Kong, going from not being familiar with the proposed technology to having an interactive demonstration mock-up on display to increase public and industry awareness. Overall, the first phase of the CIC project has been successfully completed further validating the applicability of the proposed methodological approach. Therefore, this dissertation will inspire and guide the construction industry in Hong Kong and beyond while they attempt to develop practical and marketable OCR technologies in the future.

References

‘A modern history of Hong Kong’ (2004) *Choice Reviews Online*. doi: 10.5860/choice.42-2366.

Aasrud, A., Baron, R. and Karousakis, K. (2010) *Market readiness: building blocks for market approaches*. Paris.

Abadi, M. (2005) *Issues and challenges in communication within design teams in the construction industry:: Investigation into the use of virtual teams and information and communication technologies (ICTs) in the UK construction industry*. University of Manchester.

Abernathy, W. J. and Clark, K. B. (1985) ‘Innovation: Mapping the winds of creative destruction’, *Research Policy*. doi: 10.1016/0048-7333(85)90021-6.

Ackermann, F. and Eden, C. (2011) ‘Strategic Management of Stakeholders: Theory and Practice’, *Long Range Planning*. doi: 10.1016/j.lrp.2010.08.001.

Actyx (2019) *Programming collaborative systems for machines and humans*. Available at: https://www.actyx.com/ (Accessed: 28 May 2019).

Aghion, P. and Howitt, P. (2006) ‘Joseph Schumpeter lecture: Appropriate growth policy: A unifying framework’, in *Journal of the European Economic Association*. doi: 10.1162/jeea.2006.4.2-3.269.

Akintoye, A. and Skitmore, M. (1991) ‘Profitability of UK construction contractors’, *Construction Management and Economics*. doi: 10.1080/01446199100000025.

Allen, Booz and Hamilton (1982) *New products management for the 1980s*. Booz, Allen & Hamilton.

Anderson, F. and Manseau, A. (1999) ‘A systemic approach to generation/transmission/use of innovation in construction activities’, in *The Third International Conference on Technology Policy and Innovation: Global Knowledge Partnership ĺC Creating Value for the 21st Century*. Austin, Texas, United States.

Andrew M, R. (1989) ‘Acquisition and retention of skills’, in McMillan, G. R. et al. (eds) *Applications of Human Performance Models to System Design*. Boston: Springer, pp. 419–426. doi: https://doi.org/10.1007/978-1-4757-9244-7.

Anumba, C. J., Baugh, C. and Khalfan, M. M. A. (2002) ‘Organisational structures to support concurrent engineering in construction’, *Industrial Management and Data Systems*. doi: 10.1108/02635570210428294.

Ardayfio, D. D. (1987) *Fundamentals of robotics*. Marcel Dekker, INC.

Arditi, D. (1983) 'Diffusion of network planning in construction', *Journal of Construction Engineering and Management*, 109(1), pp. 1–12.

Arditi, D., Kale, S. and Tangkar, M. (1997) 'Innovation in construction equipment and its flow into the construction industry', *Journal of Construction Engineering and Management*. doi: 10.1061/(ASCE)0733-9364(1997)123:4(371).

Arsanjani, A. (2004) 'Service-oriented modeling and architecture', *IBM developer works*. doi: 10.1109/SCC.2006.93.

Asadi, E., Li, B. and Chen, I. M. (2018) 'Pictobot: A Cooperative Painting Robot for Interior Finishing of Industrial Developments', *IEEE Robotics and Automation Magazine*. doi: 10.1109/MRA.2018.2816972.

Ayres, R. (1981) 'The impacts of industrial robots', *Carnegie Melon University*.

Azadm, M. (1988) 'The Role of Human Factors in Expert Systems Design and Acceptance', *Human Factors: The Jpurnal of the Human Factors and Ergonomics Society*, 30(4), pp. 395–414.

Baddeley, A. (1992) 'Working memory', *Science*. doi: 10.1126/science.1736359.

Baiden, B. K., Price, A. D. F. and Dainty, A. R. J. (2006) 'The extent of team integration within construction projects', *International Journal of Project Management*. doi: 10.1016/j.ijproman.2005.05.001.

Barbosa, F. *et al.* (2017) *Reinventing construction through a productivity revolution, McKinsey, Capital Projects and Infrastructure Report*.

Barlow, J. (2000) 'Innovation and learning in complex offshore construction projects', *Research Policy*. doi: 10.1016/s0048-7333(00)00115-3.

Bauer, A., Wollherr, D. and Buss, M. (2008) 'Human-robot collaboration: A survey', *International Journal of Humanoid Robotics*. doi: 10.1142/S0219843608001303.

Bhanoday Reddy, V. (2015) *Evaluation of robot structures: For applications that require high performance, safety and low energy consumption*. Mälardalen University.

Biazzo, S. (2009) 'Flexibility, structuration, and simultaneity in new product development', *Journal of Product Innovation Management*. doi: 10.1111/j.1540-5885.2009.00662.x.

Biggs, G. and Macdonald, B. (2003) 'A Survey of Robot Programming Systems', *Proceedings of the Australasian conference on robotics and automation*. doi: 10.1109/ROBOT.2001.932554.

Blayse, A. M. and Manley, K. (2004) ‘Key influences on construction innovation’, *Construction Innovation*. doi: 10.1108/14714170410815060.

Bock, T. (1988) ‘ROBOT-ORIENTED DESIGN’, in *The 5th International Symposium on Robotics in Construction*. Tokyo, Japan.

Bock, T. and Linner, T. (2016) *Site Automation: Automated/Robotic On-Site Factories*, *Site Automation: Automated/Robotic On-Site Factories*. doi: 10.1017/CBO9781139872027.

Boehm, B. and Bose, P. (1994) ‘Collaborative spiral software process model based on Theory W’, in *International Conference on the Software Process, Proceeding*. doi: 10.1109/spcon.1994.344423.

Boothroyd, G. (1994) ‘Product design for manufacture and assembly’, *Computer-Aided Design*. doi: 10.1016/0010-4485(94)90082-5.

Borjas, J, G. (2010) *Labor Economics*. Sixth. McGraw-Hill.

Bresnen, M. and Marshall, N. (2000) ‘Partnering in construction: A critical review of issues, problems and dilemmas’, *Construction Management and Economics*. doi: 10.1080/014461900370852.

Broadbent, D. E. (1958) *Perception and communication*. PERGAMON PRESS.

Brugali, D. *et al.* (2010) *Design principles, implementation guidelines, evaluation criteria for system openness and flexibility and use case implementations*.

Bucklin, L. P. and Sengupta, S. (1993) ‘Organizing Successful Co-Marketing Alliances’, *Journal of Marketing*. doi: 10.2307/1252025.

Bussiness Environment Council (2013) *Moving the Construction Sector towards Sustainable Development: Industry Engagement in Developing Corporate Sustainability Initiatives for SMEs in Construction Sector in Hong Kong- Recommendation Paper*. Hong Kong. Available at: https://bec.org.hk/files/images/Resource_Centre/Publications/SDF_RP_en_flip_version.pdf.

Bφdker, S., Grφnbæk, K. and Kyng, M. (1995) ‘Cooperative Design: Techniques and Experiences From the Scandinavian Scene’, in *Readings in Human–Computer Interaction*. doi: 10.1016/b978-0-08-051574-8.50025-x.

Capilla, R., Ali Babar, M. and Pastor, O. (2012) ‘Quality requirements engineering for systems and software architecting: Methods, approaches, and tools’, *Requirements Engineering*. doi: 10.1007/s00766-011-0137-9.

Chan, D. W. M. and Chan, A. P. C. (2002) ‘Public housing construction in hong kong: A review of its design and construction innovations’, *Architectural Science Review*. doi:

10.1080/00038628.2002.9696950.

Cheng, K., Jackson, L. and Lee, W. (2017) *Advancing 21st Century Competencies in Hong Kong*. Hong Kong. Available at: https://asiasociety.org/sites/default/files/21st-century-competencies-hong-kong.pdf.

China Daily (2012) *Meeting challenges of HK's construction industry*. Available at: http://www.chinadaily.com.cn/hkedition/2012-12/14/content_16016231.htm.

China Daily (2019) *Greater Bay Area set to boost HK development*. Available at: https://global.chinadaily.com.cn/a/201906/24/WS5d1009b9a3103dbf14329c20.html (Accessed: 5 June 2019).

Chiu, S. W. K., Ho, K. C. and Lui, T. L. (2018) *City states in the global economy: Industrial restructuring in Hong Kong and Singapore*, *City States in the Global Economy: Industrial Restructuring in Hong Kong and Singapore*. doi: 10.4324/9780429501609.

Cho, H. and LaRose, R. (1999) 'Privacy issues in internet surveys', *Social Science Computer Review*. doi: 10.1177/089443939901700402.

Choi, J. C. W. (1998) *A Comparative Study on Architectural Design between the Harmony Block and Concord Block*. The Hong Kong Polytechnic University.

Choudhry, R. M. (2017) 'Achieving safety and productivity in construction projects', *Journal of Civil Engineering and Management*. doi: 10.3846/13923730.2015.1068842.

Chowdhury, P. P. (2013) 'Key strategies and issues of positioning : A review of past studies', *American Academic & Scholarly Research Journal*.

CIC (2018) *Skilled Construction Workers Forecast (2018-2022)*. Available at: http://www.cic.hk/cic_data/files/CICMF_en_17w.pdf (Accessed: 3 May 2019).

CIC (2019a) *Construction Industry Council Releases 'Construction Expenditure Forecast and Manpower Forecast'*, *CONSTRUCTION EXPENDITURE FORECAST*. Available at: http://www.cic.hk/common/Fore/Fore.aspx?lang=en-US&year=2017_18 (Accessed: 27 November 2019).

CIC (2019b) *Construction Innovation and Technology Fund*. Available at: https://www.citf.cic.hk/ (Accessed: 3 April 2019).

CIC (2019c) *Construction Workers Registration System*. Available at: http://www.cic.hk/eng/main/registration_services/CWRS/ (Accessed: 2 March 2019).

Civil Engineering Development Department (2019) *Enhancing Land Supply Strategy - Reclamation* *outside Victoria Harbour and Rock Cavern Development*. Available at: https://www.cedd.gov.hk/eng/our-projects/project-reports/index-id-4.html (Accessed: 8 February 2019).

Clarkson, M. B. E. (1994) 'A risk based model of stakeholder theory', in *Proceedings of the Second Toronto Conference on Stakeholder Theory*.

Les Companions (2019) *PACO*. Available at: https://lescompanions.com/ (Accessed: 20 January 2020).

Connelly, M. N. and Willis, J. E. (1968) *The Development of a Human Effectiveness Function Allocation Methodology (HEFAM)*. San Diego. Available at: https://files.eric.ed.gov/fulltext/ED054310.pdf.

Construction Industry Council (2012) *Guidelines on the adoption of the pay for safety scheme*. Hong Kong. Available at: http://www.cic.hk/files/page/50/PFSS_eng_final.pdf.

Construction Industry Council (2017) *Potential Utilisation of Prefabrication Yards and Prefabricated Components in Hong Kong, Feasibility Report*. Hong Kong. Available at: http://www.cic.hk/files/page/56/Potential Utilisation of Prefabrication Yards and Prefabricated Components in HK.pdf.

Construction Industry Council (2019) *MiC*. Available at: http://www.cic.hk/eng/main/mic/whatsmic/aboutmic/ (Accessed: 5 February 2019).

Construction Robotics (2019) *SAM100*. Available at: https://www.construction-robotics.com/sam100 (Accessed: 6 May 2019).

Cravens, D. W., Piercy, N. F. and Prentice, A. (2000) 'Developing market-driven product strategies', *Journal of Product & Brand Management*. doi: 10.1108/10610420010356975.

Cronshaw, M., Cubbin, J. and Davis, E. (1990) 'The importance of product positioning: successful entry in the national newspaper market', *Business Strategy Review*. doi: 10.1111/j.1467-8616.1990.tb00016.x.

Czerwinski, S. E. *et al.* (1999) 'An architecture for a secure service discovery service', in. doi: 10.1145/313451.313462.

Dai, J. *et al.* (2009) 'Latent structures of the factors affecting construction labor productivity', *Journal of Construction Engineering and Management*. doi: 10.1061/(ASCE)0733-9364(2009)135:5(397).

Dainty, A. R. J., Briscoe, G. H. and Millett, S. J. (2001) 'Subcontractor perspectives on supply chain alliances', *Construction Management and Economics*. doi: 10.1080/01446190110089727.

Darian W, U. and Steven D, E. (2002) *Planning Design Iterations*. Available at: https://dspace.mit.edu/bitstream/handle/1721.1/4037/IMST016.pdf?sequence=2&isAllowed=y.

Demographia (2018) *15th Annual Demographia International Housing Affordability Survey: 2019 Rating Middle-Income Housing Affordability*. Available at: http://demographia.com/media_rls_2019.pdf (Accessed: 22 February 2019).

Development Bureau (2019) *List of Approved Contractors for Public Works*. Available at: https://www.devb.gov.hk/Contractor.aspx?section=80&lang=1 (Accessed: 4 June 2019).

Dibb, S. and Simkin, L. (1991) 'Targeting, Segments and Positioning', *International journal of retail & Distribution management*. doi: 10.1108/09590559110143800.

Dickson, P. R. (1992) 'Toward a General Theory of Competitive Rationality', *Journal of Marketing*. doi: 10.2307/1252133.

DISTRELEC (2019) *A GUIDE TO ROBOTICS AND AUTOMATION*. Available at: https://www.distrelec.de/medias/robotics-guide-en.pdf (Accessed: 7 March 2019).

Dörfler, K. *et al.* (2016) 'Mobile Robotic Brickwork', in *Robotic Fabrication in Architecture, Art and Design 2016*. doi: 10.1007/978-3-319-26378-6_15.

Dorine, A., Blair, N. and Jennifer, P. (2007) 'Conducting Research on the Internet: Online Survey Design, Development and Implementation Guidelines', *International Journal of Human-Computer Interaction,* 16(2), pp. 185–210. Available at: Using the Internet to conduct quantitative research presents challenges not found in conventional%0Aresearch. Some of our knowledge concerning the effective design and use of paper-based surveys%0Adoes translate into electronic formats. However, electroni.

Dragoni, N. *et al.* (2017) *Microservices: Yesterday, Today, and Tomorrow*. Edited by M. Mazzara and B. Meyer. Springer.

Dubois, A. and Gadde, L. E. (2002) 'The construction industry as a loosely coupled system: Implications for productivity and innovation', *Construction Management and Economics*. doi: 10.1080/01446190210163543.

Eastman, C. M. and Sacks, R. (2008) 'Relative productivity in the AEC industries in the United States for on-site and off-site activities', *Journal of Construction Engineering and Management*. doi: 10.1061/(ASCE)0733-9364(2008)134:7(517).

Ebert, C. (2008) *Systematisches Requirements Engineering: Anforderungen ermitteln, dokumentieren, analysieren und verwalten, 5*.

Echelmeyer, W. *et al.* (2011) 'Performance Indicators for Robotics Systems in Logistics Applications', *IROS Workshop on Metrics and Methodologies for Autonomous Robot Teams in Logistics (MMART-*

LOG).

Elattar, S. M. S. (2008) ‘Automation and robotics in construction: Opportunities and challenges’, *Emirates Journal for Engineering Research*.

Endsley, M. R. and Kaber, D. B. (1999) ‘Level of automation effects on performance, situation awareness and workload in a dynamic control task’, *Ergonomics*. doi: 10.1080/001401399185595.

Erdogmus, H. and Williams, L. (2003) ‘The economics of software development by pair programmers’, *Engineering Economist*. doi: 10.1080/00137910309408770.

Everett, J. G. and Frank, P. B. (1996) ‘Costs of accidents and injuries to the construction industry’, *Journal of Construction Engineering and Management*. doi: 10.1061/(ASCE)0733-9364(1996)122:2(158).

Everett, J. G. and Slocum, A. H. (1994) ‘Automation and robotics opportunities: Construction versus manufacturing’, *Journal of Construction Engineering and Management*. doi: 10.1061/(ASCE)0733-9364(1994)120:2(443).

FBR (2019) *Robotic construction is here*. Available at: https://www.fbr.com.au/view/hadrian-x (Accessed: 7 May 2019).

Fernandez, J. A. (2010) ‘Contextual Role of TRLs and MRLs in Technology Management’, *Sandia Report SAND2010-7595*.

Fitts, P. (1951) ‘Human engineering for an effective air navigation and traffic control system’, *Ohio State Univ.*

Fraunhofer (2019) *SIRIUS Facade Cleaning Robot*. Available at: https://www.iff.fraunhofer.de/en/business-units/robotic-systems/facade-cleaning-sirius.html (Accessed: 12 June 2019).

Freeman, R. E. and David, L. R. (1983) ‘Stockholders and Stakeholders: A New Perspective on Corporate Governance’, *California Management Review*. doi: 10.2307/41165018.

Fryman, J. and Matthias, B. (2012) ‘Safety of Industrial Robots: From Conventional to Collaborative Applications’, in *Robotics; Proceedings of ROBOTIK 2012; 7th German Conference on*.

Fung, V. K. (2019) *Creating the Greater Bay Area of the Future – Opportunities for Hong Kong*. Available at: http://www.2022foundation.com/images/GBA_MainReport.pdf (Accessed: 1 September 2019).

Furuhjelm, J. *et al.* (2017) *Owning the Sky with Agile: Building a Jet Fighter Faster, Cheaper, Better* *with Scrum*. San Diego. Available at: https://www.scruminc.com/wp-content/uploads/2015/09/Release-version_Owning-the-Sky-with-Agile.pdf.

Gambao, E., Hernando, M. and Surdilovic, D. (2008) ‘Development of a Semi-Automated Cost-Effective Facade Cleaning System’, in *Robotics and Automation in Construction*. doi: 10.5772/6190.

Gann, D. (2001) ‘Putting academic ideas into practice: technological progress and the absorptive capacity of construction organizations’, *Construction Management and Economics*. doi: 10.1080/01446190010020480.

Gann, D. M. and Ammon, S. (1998) ‘Learning and innovation management in project-based, service-enhanced firms’, *International Journal of Innovation Management*, 2(04), pp. 431–454.

Gann, D. M. and Salter, A. J. (2000) ‘Innovation in project-based, service-enhanced firms: The construction of complex products and systems’, *Research Policy*. doi: 10.1016/s0048-7333(00)00114-1.

Gann, R. G. *et al.* (1997) *Innovation in the Japanese Construction Industry: A 1995 Appraisal*. Washington: National Institute of Standards and Technology. Available at: https://nvlpubs.nist.gov/nistpubs/Legacy/SP/nistspecialpublication898.pdf.

Géron, A. (2019) *Hands-on machine learning with Scikit-Learn and TensorFlow: concepts, tools, and techniques to build intelligent systems, Hands-on machine learning with Scikit-Learn and TensorFlow: concepts, tools, and techniques to build intelligent systems*.

GGR Group (2019) *GGR*. Available at: https://www.ggrgroup.com/ (Accessed: 8 October 2019).

Gibb, A. (1999) *Off site fabrication- prefabrication, preassembly and modularisation, Whittles Publishing*.

Gibb, A., Leaviss, J. and Bust, P. (2013) ‘Older construction workers: Needs and abilities’, in *Proceedings 29th Annual Association of Researchers in Construction Management Conference, ARCOM 2013*.

Gilbreth, F. B. and Lilian M, G. (1924) *Classifying the elements of work*.

Girardet, H. (1990) ‘The metabolism of cities’, *The living city: towards a sustainable future*. doi: 10.4324/9780429197307-11.

Gloger, B. (2016) ‘Scrum - Produkte zuverlässig und schnell entwickeln’, in *Scrum - Produkte zuverlässig und schnell entwickeln*.

Golden G, R. and M, S. (2001) *Service Discovery Protocols and Programming*. New York: McGraw-

Hill Professional.

Gomberg, W. *et al.* (1949) 'Methods-Time Measurement.', *Industrial and Labor Relations Review*. doi: 10.2307/2519095.

Green, B. (2016) 'Productivity in Construction: Creating a Framework for the Industry To Thrive', *Ciob*. doi: 10.1111/ocr.12136.

Groover, M. P., M, W. and Nagel, R. N. (1986) *Industrial robotics: Technology, programming, and applications*. McGraw-Hill Higher Education.

Gurran, N. and Bramley, G. (2017) *Urban planning and the housing market: International perspectives for policy and practice, Urban Planning and the Housing Market: International Perspectives for Policy and Practice*. doi: 10.1057/978-1-137-46403-3.

Haas, T. C. *et al.* (2001) 'Implementing a multiskilled workforce', *Construction Management and Economics*. doi: 10.1080/01446190110050936.

Haddadin, S., Albu-Schäffer, A. and Hirzinger, G. (2010) 'Soft-tissue injury in robotics', in *Proceedings - IEEE International Conference on Robotics and Automation*. doi: 10.1109/ROBOT.2010.5509854.

Hägele, M. *et al.* (2016) 'Industrial robotics', in *Springer Handbook of Robotics*. doi: 10.1007/978-3-319-32552-1_54.

Hanna, A. S., Taylor, C. S. and Sullivan, K. T. (2005) 'Impact of extended overtime on construction labor productivity', *Journal of Construction Engineering and Management*. doi: 10.1061/(ASCE)0733-9364(2005)131:6(734).

Hassan, A. (2012) 'The Value Proposition Concept in Marketing: How Customers Perceive the Value Delivered by Firms– A Study of Customer Perspectives on Supermarkets in Southampton in the United Kingdom', *International Journal of Marketing Studies*. doi: 10.5539/ijms.v4n3p68.

Hegazy, T., Zaneldin, E. and Grierson, D. (2001) 'Improving design coordination for building projects. I: Information model', *Journal of Construction Engineering and Management*. doi: 10.1061/(ASCE)0733-9364(2001)127:4(322).

Higgin, G. and Jessop, N. (2013) *Communications in the building industry: the report of a pilot study*. Routledge.

HKSTP (2019) *HKSTP Officially Opens Robotics Catalysing Centre to Raise Hong Kong's Profile as a Regional Robotics Hub*. Available at: https://www.hkstp.org/en/about-us/press-room/hkstp-officially-opens-robotics-catalysing-centre-to-raise-hong-kong-s-profile-as-a-regional-robotics-hub/ (Accessed: 27 February 2019).

Ho, Paul H K (2016) 'Engineering, Construction and Architectural Management Labour and skill shortages in Hong Kong's construction industry Labour and skill shortages in Hong Kong's construction industry', *Engineering, Construction and Architectural Management Iss Construction and Architectural Management*.

Ho, Paul H.K. (2016) 'Labour and skill shortages in Hong Kong's construction industry', *Engineering, Construction and Architectural Management*. doi: 10.1108/ECAM-12-2014-0165.

Holumyong, C. *et al*. (2018) 'The Access to Antenatal and Postpartum Care Services of Migrant Workers in the Greater Mekong Subregion: The Role of Acculturative Stress and Social Support', *Journal of Pregnancy*. doi: 10.1155/2018/9241923.

Hong Kong Construction Association (2012) *Hong Kong's Construction Industry Vision 2020*. Available at: https://s3.ap-southeast-1.amazonaws.com/hkca.com.hk/upload/doc/publication/香港建造業展望2020+%28英文版本%29-XCXRT.pdf (Accessed: 21 July 2019).

Hong Kong Housing Authority (2018a) *Annual Report 2017/2018*. Available at: https://www.housingauthority.gov.hk/mini-site/haar1718/en/dlpdf.html (Accessed: 14 December 2018).

Hong Kong Housing Authority (2018b) *Number of Applications and Average Waiting Time for Public Rental Housing*. Available at: https://www.housingauthority.gov.hk/en/about-us/publications-and-statistics/prh-applications-average-waiting-time/index.html (Accessed: 22 February 2019).

Hong Kong Housing Authority (2019) *Standard Block Typical Floor Plans*. Available at: https://www.housingauthority.gov.hk/en/global-elements/estate-locator/standard-block-typical-floor-plans/index.html (Accessed: 3 May 2019).

Hong Kong Institute of Construction (2017) *Enhanced Construction Manpower Training Scheme*. Available at: http://www.hkic.edu.hk/eng/programmes/enhanced_construction_manpower_training_scheme (Accessed: 20 March 2018).

Hong Kong Institute of Construction (2019) *Cooperative Training Scheme*. Available at: https://www.hkic.edu.hk/eng/programmes/cooperative_training_scheme (Accessed: 12 January 2019).

Hong Kong Labour Department (2019) *Supplementary Labour Scheme (SLS)*. Available at: https://www.labour.gov.hk/eng/plan/iwSLS.htm (Accessed: 13 February 2019).

Hong Kong Maritime and Port Board (no date). Available at: https://www.hkmpb.gov.hk/en/about-us.html (Accessed: 22 January 2020).

Hui, E. C. M. (2001) 'Measuring affordability in public housing from economic principles: Case study of Hong Kong', *Journal of Urban Planning and Development*. doi: 10.1061/(ASCE)0733-9488(2001)127:1(34).

I.A. Motawa, A. D. F. P. and W. S. D. (1999) 'Implementing construction innovations', *15th Annual ARCOM Conference*.

Ikeda, Y. and Harada, T. (2006) 'Application of the automated building construction system using the conventional construction method together', in *2006 Proceedings of the 23rd International Symposium on Robotics and Automation in Construction, ISARC 2006*. doi: 10.22260/isarc2006/0134.

Innovation and Technology Commission (2019) *Innovation and Technology Fund*. Available at: https://www.itf.gov.hk/l-eng/about.asp (Accessed: 4 February 2019).

ITF (2019) *About the innovation and Technology Fund*. Available at: https://www.itf.gov.hk/l-eng/about.asp (Accessed: 2 August 2019).

Iuga, M. V. and Kifor, C. V. (2014) 'Lean manufacturing and its transfer to non-Japanese organizations', *Quality - Access to Success*.

Jaillon, L. and Poon, C. S. (2009) 'The evolution of prefabricated residential building systems in Hong Kong: A review of the public and the private sector', *Automation in Construction*. doi: 10.1016/j.autcon.2008.09.002.

James W, G. (2012) *Agile Requirements, Estimation and Planning-Iteration Zero*. Boston. Available at: http://www.renaissancesoftware.net/files/esc/ESC-404Paper_Grenning-Iteration0-v1r0.pdf.

Javed, A. A. *et al.* (2018) 'A systemic exploration of drivers for and constraints on construction productivity enhancement', *Built Environment Project and Asset Management*. doi: 10.1108/BEPAM-10-2017-0099.

Jernigan, F. E. (2008) *Big BIM, Little Bim: The Practical Approach to Building Information Modeling : Integrated Practice Done the Right Way!* 4site Press.

Jordan, N. (1963) 'Allocation of functions between man and machines in automated systems', *Journal of Applied Psychology*. doi: 10.1037/h0043729.

Kannan, P. K., Chang, A.-M. and Whinston, A. B. (1998) 'Marketing information on the I-Way Citation metadata', in *Communications of the ACM*. ssociation for Computing Machinery, Inc.

Kehoe, C. M. and Pitkow, J. E. (1996) 'Surveying the territory: GVU's five WWW user surveys', *The World Wide Web Journal*.

Kendall, S. and Teicher, J. (2010) *Residential open building*, *Residential Open Building*. doi:

10.4324/9780203056769.

Kevin, F., Mooz, H. and Cotterman, H. (2000) *Visualizing project management: a model for business and technical success*. 2nd edn. Edited by John Wiley and Sons.

Khoshnevis, B. *et al.* (2006) 'Mega-scale fabrication by Contour Crafting', *International Journal of Industrial and Systems Engineering*. doi: 10.1504/IJISE.2006.009791.

Kines, P., Spangenberg, S. and Dyreborg, J. (2007) 'Prioritizing occupational injury prevention in the construction industry: Injury severity or absence?', *Journal of Safety Research*. doi: 10.1016/j.jsr.2006.09.002.

Korah, T. and Rasmussen, C. (2008) 'Analysis of building textures for reconstructing partially occluded facades', in *Lecture Notes in Computer Science (including subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics)*. doi: 10.1007/978-3-540-88682-2-28.

Koskela, L. and Vrijhoef, R. (2001) 'Is the current theory of construction a hindrance to innovation?', *Building Research and Information*. doi: 10.1080/09613210110039266.

Kotler, P. *et al.* (2005) *Principles of Marketing European Edition, World Wide Web Internet and Web Information Systems*. doi: 10.2307/1250103.

Kotler, P. and Keller, K. L. (2016) *A Framework for Marketing Management*, *Marketing Management*.

KPMG (2019) *KPMG Innovative Startup Centre*. Available at: https://home.kpmg/cn/en/home/about/offices/kpmg-innovative-startup-centre.html (Accessed: 4 February 2020).

KPMG Huazhen LLP (2019) *Greater Bay Area Update*. Available at: https://assets.kpmg/content/dam/kpmg/cn/pdf/en/2019/02/gba-outline-development-plan-1.pdf (Accessed: 3 January 2020).

Kumaraswamy, M. and Dulaimi, M. (2001) 'Empowering innovative improvements through creative construction procurement', *Engineering, Construction and Architectural Management*. doi: 10.1108/eb021193.

Labour Department (2018) *A Concise Guide to the Employees' Compensation Ordinance (with Frequently Asked Questions on Common Employees' Compensation Issues)*. Available at: https://www.labour.gov.hk/eng/public/ecd/pco360.pdf (Accessed: 22 February 2019).

Labour Department (2019) *Employees' Compensation Ordinance*. Available at: https://www.labour.gov.hk/eng/legislat/content1.htm (Accessed: 25 July 2019).

Lampe, A. and Chatila, R. (2006) ‘Performance measure for the evaluation of mobile robot autonomy’, in *Proceedings - IEEE International Conference on Robotics and Automation*. doi: 10.1109/ROBOT.2006.1642325.

Lange, F. *et al.* (2012) ‘Revised force control using a compliant sensor with a position controlled robot’, in *Proceedings - IEEE International Conference on Robotics and Automation*. doi: 10.1109/ICRA.2012.6224630.

Lee, C. *et al.* (2008) *Final report of the Construction Industry Institute, Hong Kong research project on reinventing the Hong Kong construction industry for its sustainable development*. Hong Kong. Available at: http://hdl.handle.net/10397/2371.

Lee, H. M. and Kim, J. B. (2013) ‘A survey on robot teaching: Categorization and brief review’, in *Applied Mechanics and Materials*. doi: 10.4028/www.scientific.net/AMM.330.648.

Lee, J. and Ngai-ming, Y. (2006) ‘Public housing and family life in East Asia: Housing history and social change in Hong Kong, 1953-1990’, *Journal of Family History*. doi: 10.1177/0363199005283008.

Lee, M. C., To Chang and Chang Chien, W. T. (2011) ‘An Approach for Developing Concept of Innovation Readiness Levels’, *International Journal of Managing Information Technology*. doi: 10.5121/ijmit.2011.3203.

Leslie, C. and Nobuyasu, M. (1998) *Construction robots: the search for new building technology in Japan*. ASCE Publications.

Lewis, M. (1998) ‘Designing for Human-Agent Interaction’, *AI Magazine*.

Lewis, W. A. (2013) *The theory of economic growth*, *The Theory of Economic Growth*. doi: 10.4324/9780203709665.

Li, R. Y. M. (2018) *An Economic Analysis on Automated Construction Safety*, *An Economic Analysis on Automated Construction Safety*. doi: 10.1007/978-981-10-5771-7.

Likert, R. (1932) ‘A technique for the measurement of attitudes’, *Archives of Psychology*.

Lindsey, Q., Mellinger, D. and Kumar, V. (2012) ‘Construction of cubic structures with quadrotor teams’, in *Robotics: Science and Systems*. doi: 10.7551/mitpress/9481.003.0028.

Linner, T. *et al.* (2020) ‘A technology management system for the development of single-task construction robots’, *Construction Innovation*, 20, pp. 96–111.

Lipman, R. (2017) ‘STEP File Analyzer Software’, *Journal of Research of the National Institute of Standards and Technology*. doi: 10.6028/jres.122.016.

Liu, H. *et al.* (2017) 'Deepfacade: A deep learning approach to facade parsing', in *IJCAI International Joint Conference on Artificial Intelligence*. doi: 10.24963/ijcai.2017/320.

Long, J., Shelhamer, E. and Darrell, T. (2015) 'Fully convolutional networks for semantic segmentation', in *Proceedings of the IEEE Computer Society Conference on Computer Vision and Pattern Recognition*. doi: 10.1109/CVPR.2015.7298965.

Maertens, J. A. *et al.* (2012) 'Physical Capabilities and Occupational Health of Older Workers', in *The Oxford Handbook of Work and Aging*. doi: 10.1093/oxfordhb/9780195385052.013.0089.

Majava, J., Harkonen, J. and Haapasalo, H. (2015) 'The relations between stakeholders and product development drivers: Practitioners' perspectives', *International Journal of Innovation and Learning*. doi: 10.1504/IJIL.2015.066064.

Mankins, J. C. (1995) *Technology readiness levels: A white paper*.

Martinez, S. *et al.* (2008) 'Building industrialization: Robotized assembly of modular products', *Assembly Automation*. doi: 10.1108/01445150810863716.

Martinović, A. *et al.* (2012) 'A Three-Layered Approach to Facade Parsing - Supplementary Material', *Eccv2012*. doi: 10.1007/978-3-642-33786-4_31.

Meyer, M. H. and Lehnerd, A. P. (1997) 'The power of product platforms', *The Free Press*.

Miller, J. A. *et al.* (2016) 'Open source big data analytics frameworks written in scala', in *Proceedings - 2016 IEEE International Congress on Big Data, BigData Congress 2016*. doi: 10.1109/BigDataCongress.2016.61.

Miozzo, M. and Dewick, P. (2004) 'Networks and innovation in European construction: Benefits from inter-organisational cooperation in a fragmented industry', *International Journal of Technology Management*. doi: 10.1504/IJTM.2004.003882.

Mitchell, R. K., Agle, B. R. and Wood, D. J. (1997) 'Toward a theory of stakeholder identification and salience: Defining the principle of who and what really counts', *Academy of Management Review*. doi: 10.5465/AMR.1997.9711022105.

Mohamad, M. I. (1999) *The application of concurrent engineering philosophy to the construction industry*. Loughborough University.

Müller, A. C. and Guido, S. (2015) *Introduction to Machine Learning with Python and Scikit-Learn, O'Reilly Media, Inc.*

Nanyam, V. N. *et al.* (2015) 'Selection Framework for Evaluating Housing Technologies', in *Procedia*

Engineering. doi: 10.1016/j.proeng.2015.10.044.

Narver, J. C. and Slater, S. F. (1990) 'The Effect of a Market Orientation on Business Profitability', *Journal of Marketing*. doi: 10.2307/1251757.

Nelson, P. A. and Stephen J, E. (1991) *Active control of sound*. London: Academic Press.

nlink (2019) *nlink advanced mobile robotics*. Available at: https://www.nlink.no (Accessed: 9 May 2019).

Nüchter, A., Elseberg, J. and Borrmann, D. (2013) 'Irma3D - An intelligent robot for mapping applications', in *IFAC Proceedings Volumes (IFAC-PapersOnline)*. doi: 10.3182/20131111-3-KR-2043.00011.

Nwana, H. S. (1996) 'Software agents: an overview', *The Knowledge Engineering Review*. doi: 10.1017/s026988890000789x.

Nygard, C. H., Luopajarvi, T. and Ilmarinen, J. (1991) 'Musculoskeletal capacity and its changes among aging municipal employees in different work categories', *Scandinavian Journal of Work, Environment and Health*.

Nykiforuk, C. *et al.* (2011) *Policy readiness tool: Understanding a municipality's readiness for policy change and strategies for taking action*. Edmonton, Alberta.

O-Matic (2019) *O-Matic robot intelligent robot limited*. Available at: http://www.o-matic.cn/ (Accessed: 30 April 2019).

O'Meara, C., Schlag, L. and Wickler, M. (2018) 'Applications of Deep Learning Neural Networks to Satellite Telemetry Monitoring', in *SpaceOps Conferences*. Marseille, France, p. 2558.

OKIBO (2019) *Smart robotics for construction sites*. Available at: https://okibo.com/ (Accessed: 30 April 2019).

Ortt, J. R., Langley, D. J. and Pals, N. (2015) 'Ten niche strategies to commercialize new high-tech products', in *2013 International Conference on Engineering, Technology and Innovation, ICE 2013 and IEEE International Technology Management Conference, ITMC 2013*. doi: 10.1109/ITMC.2013.7352687.

OSD Manufacturing Technology Program (2010) *Manufacturing readiness level deskbook*, *Best Practice*.

Osterwalder, A. *et al.* (2014) *Value proposition design: How to create products and services customers want*. John Wiley & Son, inc.

Palaneeswaran, E. *et al.* (2008) 'Mapping rework causes and effects using artificial neural networks', *Building Research and Information*. doi: 10.1080/09613210802128269.

Pan, Wen *et al.* (2018) 'A methodological approach to implement on-site construction robotics and automation: a case of Hong Kong', in *the 35th International Symposium on Automation and Robotics in Construction (ISARC)*.

Pan, W. *et al.* (2019) 'Developing a roadmap for implementing on-site construction automation and robotics in Hong Kong', in *Proceedings of CIB World Building Congress 2019 'Constructing Smart Cities' (CIB WBC 2019)*.

Pan, W., Gibb, A. G. and Dainty, A. R. (2008) 'A decision support matrix for build system selection in housing construction', *International Journal for Housing Science and Its Applications*.

Pan, W., Ilhan, B. and Bock, T. (2018) 'Process information modelling for public housing construction project in Hong Kong', in. doi: 10.3311/ccc2018-011.

Pan, W., Langosch, K. and Bock, T. (2017) 'Development of the Process Information Modelling in the construction project: A case study of the zero-plus project', in *ISARC 2017 - Proceedings of the 34th International Symposium on Automation and Robotics in Construction*. doi: 10.22260/isarc2017/0108.

Pan, W. and Sidwell, R. (2011) 'Demystifying the cost barriers to offsite construction in the UK', *Construction Management and Economics*. doi: 10.1080/01446193.2011.637938.

Parasuraman, R., Molloy, R. and Singh, I. L. (1993) 'Performance Consequences of Automation-Induced "Complacency"', *The International Journal of Aviation Psychology*. doi: 10.1207/s15327108ijap0301_1.

Parasuraman, R. and Riley, V. (1997) 'Humans and automation: Use, misuse, disuse, abuse', *Human Factors*. doi: 10.1518/001872097778543886.

Parasuraman, R., Sheridan, T. B. and Wickens, C. D. (2000) 'A model for types and levels of human interaction with automation', *IEEE Transactions on Systems, Man, and Cybernetics Part A:Systems and Humans*. doi: 10.1109/3468.844354.

Paun, F. (2011) 'Demand Readiness Level (DRL), a new tool to hybridize Market Pull and Technology Push approaches. Introspective analysis of the new trends in Technology Transfer practices.', *Springer Encyclopedia, Forthcoming*.

Peavey, E. K., Zoss, J. and Watkins, N. (2012) 'Simulation and mock up research methods to enhance design decision making', *Health Environments Research and Design Journal*. doi: 10.1177/193758671200500313.

Philip F, Y., Achim, M. and Neil, L. (2015) *Robotic Futures*. Shanghai: Tongji University Press.

Pistorius, C. (2017) *Innovation Insight: The Impact of Emerging Technologies on the Construction Industry*. Available at: https://www.deltahedron.co.uk/wp-content/uploads/2018/08/DeltaHedron-Innovation-Insight_Impact-of-emerging-technologies-on-construction_No-4-17-1_Aug-2017.pdf.

Planning department (2018) *Annual Report 2018*. Available at: https://www.pland.gov.hk/pland_en/press/publication/ar_18/pdf/ar2018_en.pdf (Accessed: 8 February 2019).

Poon, S. W., Tang, S. L. and Wong, F. K. W. (2008) *Management and Economics of Construction Safety in Hong Kong*. Hong Kong University Press.

Potts, J. *et al.* (2008) 'Consumer co-creation and situated creativity', *Industry and Innovation*. doi: 10.1080/13662710802373783.

Price, H. E. and Pulliam, R. (1982a) *The allocation of functions in man-machine systems*.

Price, H. E. and Pulliam, R. (1982b) *The allocation of functions in man-machine systems*. Available at: https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/19850070377.pdf.

Price, H. E. and Tabachnick, B. . (1968) *A descriptive model for determining optimal human performance in systems*.

Pries, F. and Janszen, F. (1995) 'Innovation in the construction industry: The dominant role of the environment', *Construction Management and Economics*. doi: 10.1080/01446199500000006.

Prof. John M. Bryson (2003) 'What To Do When Stakeholders Maatter A Guide to Stakeholder Identification and Analysis Tecniques', *Academy of Management Journal*. doi: 10.1016/j.lrp.2010.08.001.

Q-Bot (2019) *Q-Bot develops intelligent tools to assess and maintain the health of buildings*. Available at: https://www.q-bot.co/about (Accessed: 7 May 2019).

RAW (2019) *Robot at work*. Available at: https://robotatwork.com/ (Accessed: 9 May 2019).

Research Office Legislative Council Secretariat (2018) *Construction industry in Hong Kong, statistical highlights*. Available at: https://www.legco.gov.hk/research-publications/english/1819issh07-construction-industry-in-hong-kong-20181121-e.pdf (Accessed: 15 October 2018).

Richard, R. B. (2005) 'Industrialised building systems: Reproduction before automation and robotics', in *Automation in Construction*. doi: 10.1016/j.autcon.2004.09.009.

Robert G, C. (2011) *Winning at new products: Creating value through innovation*. Basic Books.

Robertson, S. and Robertson, J. (2013) 'Mastering the Requirements Process Getting Requirements Right', *Work*. doi: 0-201-36046-2.

Rowley, J. (2002) 'Using case studies in research', *Management Research News*. doi: 10.1108/01409170210782990.

Rowlinson, S. (2014) *Cost Escalation in the Hong Kong construction industry report*.

Rowlinson, S., Yip, B. and Poon, S. W. (2009) *Safety Initiative Effectiveness in Hong Kong – One Size Does Not Fit All*.

Sadin, S. R., Povinelli, F. P. and Rosen, R. (1989) 'The NASA technology push towards future space mission systems', *Acta Astronautica*. doi: 10.1016/0094-5765(89)90054-4.

Saha, S. (2019) *A Comprehensive Guide to Convolutional Neural Networks — the ELI5 way*. Available at: https://towardsdatascience.com/a-comprehensive-guide-to-convolutional-neural-networks-the-eli5-way-3bd2b1164a53 (Accessed: 12 November 2019).

Salem, O. and Zimmer, E. (2005) 'Application of lean manufacturing principles to construction', *Lean Construction Journal*.

Sauser, B. *et al.* (2006) 'From TRL to SRL: The concept of systems readiness levels', *Conference on Systems Engineering Research, Los Angeles, CA*.

Scerbo, M. W. and Ed Mouloua, M. (1999) 'Automation technology and human performance: Current research and trends', in *Conference on Automation Technology and Human Performance*. Norfolk, VA, US: Lawrence Erlbaum Associates Publishers.

Scheinman, V. and McCarthy, J. M. (2008) 'Mechanisms and Actuation', in *Springer Handbook of Robotics*. doi: 10.1007/978-3-540-30301-5_4.

Seaden, G. and Manseau, A. (2001) 'Public policy and construction innovation', *Building Research and Information*. doi: 10.1080/09613210010027701.

Sharma, S. and Mehra, R. (2019) 'Implications of Pooling Strategies in convolutional neural networks: A Deep Insight', *Foundations of Computing and Decision Sciences*. doi: 10.2478/fcds-2019-0016.

Shelhamer, E., Long, J. and Darrell, T. (2017) 'Fully Convolutional Networks for Semantic Segmentation', *IEEE Transactions on Pattern Analysis and Machine Intelligence*. doi: 10.1109/TPAMI.2016.2572683.

Sheridan, T. B. (1998) 'Allocating functions rationally between humans and machines', *Ergonomics in Design*. doi: 10.1177/106480469800600305.

Sheridan, T. B. (2001) 'Rumination on automation, 1998', *Annual Reviews in Control*. doi: 10.1016/S1367-5788(01)00009-8.

Shih, F.-L. and Jones, C. (2014) 'Introduction to Taiwan and Hong Kong in comparative perspective: centres– peripheries, colonialism, and the politics of representation', pp. 1–20. Available at: http://eprints.lse.ac.uk/59346/.

Siu, O. L., Phillips, D. R. and Leung, T. W. (2003) 'Age differences in safety attitudes and safety performance in Hong Kong construction workers', *Journal of Safety Research*. doi: 10.1016/S0022-4375(02)00072-5.

Skibiniewski, M. J. (2017) 'Current Status of Construction Automation and Robotics in the United States of America', in *9th ISARC International Symposium on Automation and Robotics in Construction*. doi: 10.22260/isarc1992/0003.

Slaughter, E. S. (1998) 'Models of construction innovation', *Journal of Construction Engineering and Management*. doi: 10.1061/(ASCE)0733-9364(1998)124:3(226).

Smart, A. (2002) 'Agents of eviction: The squatter control and clearance division of Hong Kong's housing department', *Singapore Journal of Tropical Geography*. doi: 10.1111/1467-9493.00134.

Ştefan, V. (2015) *Sequences of Niche Strategies: An Exploratory Multiple-Case Study in Automotive*. Delft University of Technology. Available at: https://pdfs.semanticscholar.org/cddf/143a01b913f290c2bd2e2d5f24149cb18376.pdf.

Steinfeld, A. *et al.* (2006) 'Common metrics for human-robot interaction', in *HRI 2006: Proceedings of the 2006 ACM Conference on Human-Robot Interaction*. doi: 10.1145/1121241.1121249.

Stender, M. (2002) 'Outline of an Agile Incremental Implementation Methodology for Enterprise Systems', *Proceedings of the Eighth Americas Conference on Information Systems*.

Svensson, M. and Hultkrantz, L. (2017) 'A Comparison of Cost-Benefit and Cost-Effectiveness Analysis in Practice: Divergent Policy Practices in Sweden', *Nordic Journal of Health Economics*. doi: 10.5617/njhe.1592.

Swevers, J. *et al.* (1997) 'Optimal robot excitation and identification', *IEEE Transactions on Robotics and Automation*. doi: 10.1109/70.631234.

Szyperski, C., Gruntz, D. and Murer, S. (2002) *Component software: beyond object-oriented programming*. 2nd edn. Pearson Education.

Taghavi, M., Iturralde, K. and Bock, T. (2018) 'Cable-driven parallel robot for curtain wall modules automatic installation', in *ISARC 2018 - 35th International Symposium on Automation and Robotics in Construction and International AEC/FM Hackathon: The Future of Building Things*. doi: 10.22260/isarc2018/0056.

Tan, J., Liu, K. and Turk, G. (2011) 'Stable proportional-derivative controllers', *IEEE Computer Graphics and Applications*. doi: 10.1109/MCG.2011.30.

Task Force on Land Supply (2018) *Land for Hong Kong : Our Home, Our Say!* Hong Kong. Available at: https://docplayer.net/102736411-Land-for-hong-kong-our-home-our-say.html.

Teece, D. J. (2008) 'Capturing value from technological innovation: Integration, strategic partnering, and licensing decisions', in *Technological Know-How, Organizational Capabilities, and Strategic Management: Business Strategy and Enterprise Development in Competitive Environments*. doi: 10.1142/9789812834478_0012.

Tenah, K. A. (2001) 'Project delivery systems for construction: An overview', *Cost Engineering (Morgantown, West Virginia)*.

Terada, Y. and Murata, S. (2008) 'Automatic modular assembly system and its distributed control', *International Journal of Robotics Research*. doi: 10.1177/0278364907085562.

Thomas, H. R. (1992) 'Effects of scheduled overtime on labor productivity', *Journal of Construction Engineering and Management*. doi: 10.1061/(ASCE)0733-9364(1992)118:1(60).

Thomas, L. (2013) *Automated and Robotic Construction: Intergrated Automated Construction Sites*. Technique University Munich.

To, C. (2016) 'A bright future for Hong Kong's construction industry', *Proceedings of the Institution of Civil Engineers: Civil Engineering*. doi: 10.1680/jcien.15.00058.

Transport and Housing Bureau (2014) *Long Term Housing Strategy*. Available at: https://www.thb.gov.hk/eng/policy/housing/policy/lths/LTHS201412.pdf (Accessed: 11 May 2019).

TyBot LLC (2019) *The autonomous rebar-tying robot*. Available at: https://www.tybotllc.com/ (Accessed: 6 May 2019).

Ueno, T. *et al.* (1986) 'Construction robots for site automation', in *CAD and Robotics in Architecture and Construction*. Boston, Marseilles: Marseilles.

Unger, D. and Eppinger, S. (2011) 'Improving product development process design: A method for managing information flows, risks, and iterations', *Journal of Engineering Design*. doi: 10.1080/09544828.2010.524886.

Vicente, K. J. and Rasmussen, J. (1992) 'Ecological Interface Design: Theoretical Foundations', *IEEE Transactions on Systems, Man and Cybernetics*. doi: 10.1109/21.156574.

Walker, D., Hampson, K. and Ashton, S. (2008) 'Developing an Innovative Culture Through Relationship-Based Procurement Systems', in *Procurement Strategies: A Relationship-based Approach*. doi: 10.1002/9780470690635.ch9.

Warszawski, A. (1985) 'Economic implications of robotics in building', *Building and Environment*. doi: 10.1016/0360-1323(85)90001-0.

White, T. (2012) *Hadoop: The Definitive Guide*. 3rd edn. O'Reilly Media, Inc. Available at: http://grut-computing.com/HadoopBook.pdf.

WIKISPEED (2019) *No Title*. Available at: http://wikispeed.org/ (Accessed: 9 August 2019).

Winch, G. (1998) 'Zephyrs of creative destruction: Understanding the management of innovation in construction', *Building Research and Information*. doi: 10.1080/096132198369751.

Wong, J., Zhang, J. and Lee, J. (2015) 'A vision of the future construction industry of Hong Kong', in *32nd International Symposium on Automation and Robotics in Construction and Mining: Connected to the Future, Proceedings*. doi: 10.22260/isarc2015/0110.

Wong, Y. C. R. (2015) *Hong Kong land for Hong Kong people: Fixing the failures of our housing policy, Hong Kong Land for Hong Kong People: Fixing the Failures of Our Housing Policy*.

Wortman, D. B., Steven D, D. and Deborah J, S. (1975) 'SAINT simulation of a remotely piloted vehicle/drone control facility', in *Human Factors Society Annual Meeting*. Human Factors Society Annual Meeting: SAGE Publications, pp. 342–346.

Yat Hung, C., Ping Chuen Albert, C. and Chi Man Eddie, H. (2002) 'Capital structure and profitability of the property and construction sectors in Hong Kong', *Journal of Property Investment & Finance*. doi: 10.1108/14635780210446469.

Yi, J. and Zhang, J. (2010) 'The effect of house price on fertility: Evidence from Hong Kong', *Economic Inquiry*. doi: 10.1111/j.1465-7295.2009.00213.x.

Yun, G. W. and Trumbo, C. W. (2006) 'Comparative Response to a Survey Executed by Post, E-mail, & Web Form', *Journal of Computer-Mediated Communication*. doi: 10.1111/j.1083-6101.2000.tb00112.x.

Zaharia, M. *et al.* (2016) 'Apache spark: A unified engine for big data processing', *Communications of the ACM*. doi: 10.1145/2934664.

Zhao, P. *et al.* (2010) 'Rectilinear parsing of architecture in urban environment', in *Proceedings of the IEEE Computer Society Conference on Computer Vision and Pattern Recognition*. doi: 10.1109/CVPR.2010.5540192.

Zinn, M., Khatib, O. and Roth, B. (2004) 'A new actuation approach for human friendly robot design', in *Proceedings - IEEE International Conference on Robotics and Automation*. doi: 10.1007/3-540-36268-1_9.