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Ambient Rehabilitation Kit: Developing Personalized Intelligent Interior Units to Achieve Demographic Sustainability in Aging Society

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Zusammenfassung

Die Überalterung der Bevölkerung und ihre Folgen sind wohl eine der größten Herausforderungen der modernen Gesellschaft. Sie ist nicht nur eine akute Krise in den Industrieländern, sondern auch eine ernsthafte Bedrohung für Schwellenländer. Viele altersbedingte Krankheiten werden durch einen Mangel an körperlichen, kognitiven und sozialen Aktivitäten begünstigt. Eine Steigerung von Aktivität und Bewegung hat viele Vorteile für ältere Erwachsene und kann ihre Unabhängigkeit verbessern. Daher müssen energische Maßnahmen zur Förderung der körperlichen Aktivität und Unabhängigkeit älterer Erwachsener ergriffen werden, um die Auswirkungen unserer alternden Gesellschaft abzumildern.

Somit lässt sich die primäre Forschungsfrage wie folgt formulieren: Wie effizient kann das neuartige Forschungsfeld des Ambient Assisted Living dazu beitragen, die Krise der Bevölkerungsüberalterung durch die Erhöhung des Aktivitäts- und Unabhängigkeitsniveaus älterer Erwachsener abzumildern? Entsprechend lässt sich die Haupthypothese dieser Dissertation formulieren: Das Ambient Rehabilitation Kit, welches mit einem systematischen Verfahrensmodell entwickelt wurde, kann das Aktivitäts- und Unabhängigkeitsniveau älterer Erwachsener erhöhen, die Pfleger von mühsamen täglichen Pflege- und Trainingsaufgaben befreien und sie in die Lage versetzen, auf psychologischer und emotionaler Ebene zu kommunizieren, um letztendlich die Auswirkungen der rapiden Bevölkerungsüberalterung auf eine erschwingliche und skalierbare Weise abzumildern. Die Hypothese wird anhand der nachfolgenden Forschungsaktivitäten überprüft.

In dieser Doktorarbeit wurde zunächst ein Verfahrensmodell als Grundlage für die effiziente und systematische Entwicklung von gerontechnologischen Systemen vorgeschlagen. Basierend auf der Analyse des Stands der Technik im Bereich Ambient Assisted Living und den Anforderungen älterer Menschen wurde ein Dienstleistungssystem konzipiert, das klinische und pflegerische Umgebungen in personalisierte modulare Erfassungs-, Präventions- und Interventionssysteme umwandelt und ältere Menschen durch verschiedene Aktivitäten zu einer gesünderen Lebensweise ermutigt. Um dieses Ziel zu erreichen, wurde eine Reihe von intelligenten Geräten entwickelt, die fortschrittliche Sensor- und Hilfstechnologien integrieren, so genannte Personalized Intelligent Interior Units, welche die Pflegekonzepte und -funktionalitäten nahtlos umsetzen. In der Zwischenzeit wurde ein flexibles, modulares Ambient Rehabilitation Kit vorgeschlagen, das die oben erwähnten Hilfstechnologien integriert, um eine einzigartige Wohn- und Pflegelösung für ältere Erwachsene in verschiedenen Lebensumgebungen zu schaffen. Zugleich wurde eine Strategie zum Testen und Ausstellen dieses Systems vorgeschlagen und ein Rahmen für die Kosten-Nutzen-Analyse des Ambient Rehabilitation Kits im Vergleich zu traditionellen Pflegemethoden in drei Szenarien untersucht, deren Ergebnisse darauf hinweisen, dass das

vorgeschlagene Ambient Rehabilitation Kit für das Gesundheitssystem in Deutschland investitionswürdig ist, um den Personalmangel im Gesundheitswesen zu lindern. Um die ernsthafte Bedrohung der sozialen Nachhaltigkeit Chinas durch die rasche Alterung der größten Volksgruppe der Welt abzumildern, wurden die Aussichten für die Implementierung des Ambient Rehabilitation Kit auf dem chinesischen Markt diskutiert und ein Forschungs- und Entwicklungsaktionsplan auf der Grundlage der Ergebnisse einer Meinungsumfrage vorgeschlagen. Schließlich wurde das vorgeschlagene System auch in einen größeren visionären Kontext eingebettet, den dynamisch-vertikalen Urbanismus, als Ausblick auf ein umfassendes städtisches Entwicklungsmodell für die Zukunft, das durch fortschrittliche Bau- und Hilfstechnologien unterstützt wird.

In den vergangenen fünf Jahren wurden die verschiedenen Komponenten dieser Doktorarbeit in mehreren Forschungsprojekten verifiziert oder validiert, unter anderem im Rahmen von REACH2020, CIC Hong Kong Consultancy Project, LISA Habitec, HEPHAESTUS und A^2L-Mobilius.

Abstract

Population aging and its consequences are arguably one of the most serious challenges facing human society. It is not only a severe crisis in the developed world, but also a rigorous threat in emerging economies. Many age-related diseases are fostered by the lack of physical, cognitive, and social activities. Increasing the activity level has many benefits for older adults and can improve their independence. Therefore, vigorous measures need to be taken to promote the activity and independence level of older adults to mitigate the impact of aging society.

Consequently, the primary research question can be formulated as such: How efficient can the novel research field of Ambient Assisted Living help mitigate the crisis of population aging by increasing older adults' activity and independence level? Accordingly, the main hypothesis of this doctoral thesis can be proposed: The Ambient Rehabilitation Kit developed with a systematic procedure model can increase older adults' activity and independence level, liberate the caregivers from tedious daily care and exercising tasks, and empower them to communicate on the psychological and emotional level, eventually mitigating the impact of rapid population aging in an affordable and scalable manner. The hypothesis will be proved by the following research activities.

This doctoral research first proposed a procedure model as the foundation to efficiently develop gerontechnology systems in a systematic manner. Based on the analysis of the state-of-the-art Ambient Assisted Living solutions and the requirements of older adults, a service system transforming clinical and care environments into personalized modular sensing, prevention, and intervention systems was proposed, encouraging older adults to become healthier through various activities. To achieve that goal, a series of smart interior devices integrating advanced sensing and assistive technology, namely Personalized Intelligent Interior Units, were developed which seamlessly materialize the care concepts and functionality. Meanwhile, a flexible modular Ambient Rehabilitation Kit integrating abovementioned assistive technologies was proposed to create a unique interior living and care solution for older adults in various living environments. At the same time, a strategy for testing and exhibiting the system was proposed. Furthermore, this research also explored a framework for the cost-benefit analysis of the Ambient Rehabilitation Kit compared to traditional care methods in three scenarios, whose results indicated that the proposed Ambient Rehabilitation Kit is worth investing by the healthcare system in Germany, soothing the labor shortage in the healthcare system. In addition, in order to mitigate the severe threat to China's social sustainability imposed by rapid population aging, the prospects for implementing the Ambient Rehabilitation Kit in China's market were discussed and a research and development action plan was proposed based on the results of an opinion survey. Finally, the proposed system was also integrated in a larger visionary

context, namely dynamic vertical urbanism, as an outlook for a comprehensive urban developing model for the future, powered by advanced construction and assistive technologies.

Throughout the past five years, the various components of this doctoral research were verified or validated in several research projects including but not limited to REACH2020, CIC Hong Kong Consultancy Project, LISA Habitec, HEPHAESTUS, and A^2L-Mobilius.

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[1] All figures were created by the author unless specified otherwise.

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List of used abbreviations

AAL – Ambient assisted living

ADLs – Activities of daily living

AEC – Architecture, engineering, and construction

AI – Artificial intelligence

ARK – Ambient Rehabilitation Kit

BCR – Benefit-cost ratio

BEP – Break-even point

BIM – Building information modeling

BMI – Body mass index

CAD – Computer-aided design

CBA – Cost-benefit analysis

CDPR – Cable-driven parallel robot

CEN – Comité Européen de Normalisation (European Committee for Standardization)

CENELEC – Comité Européen de Normalisation Électrotechnique (European Committee for Electrotechnical Standardization)

COPD – Chronic obstructive pulmonary disease

COVID-19 – Coronavirus disease 2019

CTBUH – Council on Tall Buildings and Urban Habitat

CVD – Cardiovascular disease

CWM – Curtain wall module

DIN – Deutsches Institut für Normung (German Institute for Standardization)

DVU – Dynamic Vertical Urbanism

ECG – Electrocardiography

EMG – Electromyography

ETSI – European Telecommunication Standards Institute

GCF – Ground construction factory

GUI – Graphical user interface

HVAC – Heating, ventilation and air conditioning

ICT – Information and communications technology

ICU – Intensive care unit

IEC – International Electrotechnical Commission

ISO – International Organization for Standardization

ITU – International Telecommunication Union

LED – Light-emitting diode

LSS – Life support system

MOE – Margin of error

NPV – Net present value

OECD – Organisation for Economic Co-operation and Development

OCF – On-site construction factory

PBP – Payback period

PDCA – Plan-Do-Check-Act

PI^{2}U – Personalized Intelligent Interior Unit

PIM – Process information modeling

PLC – Programmable logic controller

R&D – Research and development

RAM – Random-access memory

REACH – Responsive Engagement of the Elderly promoting Activity and Customized Healthcare

RFID – Radio frequency identification tag

ROD – Robot-Oriented Design

ROI – Return on investment

RQ – Research question

SARS-CoV-2 – Severe acute respiratory syndrome coronavirus 2

SCF – Sky construction factory

SPO2 – Saturation of peripheral oxygen

SQ – Sub-question

STCR – Single-task construction robot

STEM – Science, technology, engineering, and mathematics

STS – Sit-to-stand movement

TRL – Technical readiness level

VR – Virtual reality

WHO – World Health Organization

1 Introduction: What we talk about when we talk about population aging?

"Every day you get older. Now that's a law."

Butch Cassidy[2]

Population aging and climate change are arguably two of the greatest challenges facing human society today. This research mainly focuses on addressing the challenge of population aging by proposing a methodological framework as well as technological solution to mitigate its impact. In this chapter, the global challenge of population aging will be analyzed in detail. In the meantime, the status quo of the elderly care today will be discussed. Furthermore, the potential upcoming paradigm shift in elderly care industry will be explained. Accordingly, the questions that this thesis sets out to answer and the respective hypotheses guiding this doctoral thesis are proposed. In addition, the methodology of this doctoral research will be introduced as well. Finally, the structure of the thesis will be defined based on the proposed methodological framework.

1.1 Population aging: A gigantic Gray Rhino running towards us

Michele Wucker first defined the term Gray Rhino as "a highly probable, high-impact threat: something we ought to see coming, like a two-ton rhinoceros aiming its horn in our direction and preparing to charge" (Wucker, 2016). Unlike the Black Swan, which was popularized by Nassim Nicholas Taleb in his 2007 book The Black Swan: The Impact of the Highly Improbable as a highly improbable event with a major impact such as a terrorist attack, earthquake, and pandemic (Taleb, 2007), Gray Rhino is foreseeable and preventable, yet oftentimes neglected by people. The phenomenon of population aging can be considered as a typical Gray Rhino.

Today, the world's population is aging at an unprecedented pace. As of 2019, there are more than 7.7 billion individuals living on this planet, of which 9.1% (0.7 billion) are over 65 years old. Globally, the population aged 65 years or over is the fastest-growing age group, whose proportion increased from 6.9% in 2000 to 9.3% in 2020 and is projected to reach 15.9% by 2050 and 22.6% by 2100 (United Nations, 2019). According to the World Health Organization (WHO), "aging society", "aged society", and "super-aged society" respectively refers to societies where older population aged 65 years and over taking up 7%, 14%, and 21% of the total population (Kim and Kim, 2020). This means that the entire world

[2] Butch Cassidy: Character in the film *Butch Cassidy and the Sundance Kid* (1969).

entered an aging mode since the early 2000s and will reach the aged and super-aged status before 2050 and 2100 respectively. Moreover, the number of older adults aged 80 years or over is predicted to triple from 143 million in 2019 to 426 million in 2050 (United Nations, 2019). The general trend is that the higher the income of a country, the more serious the aging problem. Specifically, the situation of population aging varies drastically in different countries. As a result, the challenge of population aging is especially prominent in the most developed countries.

In Germany, for instance, the current percentage of population aged 65 and over has exceeded 21.7% (i.e., 18.2 million), which already met the standard of "super-aged society". In 2030, Germany will have one of the oldest populations in the world, of which only half will be in working age (i.e., aged between 25-64), and more than every fourth (i.e., 26.2%) will be 65 years or older (United Nations, 2019). There is also a gender imbalance between male and female older adults in Germany. As of the end of 2014, among the people aged 60 and over, 56% were women and 44% were men. This disparity between male and female older adults is partly due to the higher life expectancy of women. However, the impact of World War II also clearly contributed to this phenomenon since many men died young during the war. (Federal Statistical Office of Germany, 2016)

Japan is another prominent example of "super-aged society" that faces an even more serious aging situation than Germany. Due to a high life expectancy and a low fertility rate, the percentage of the Japanese population aged 65 and over reached staggering 28.4% (i.e., 35.9 million, which is nearly equal to the entire population of Canada) in 2020, and will continue to increase to 37.7% in 2050 (United Nations, 2019). In addition, Japan is also known for its population's longevity, having more than two million older adults aged 90 and over, and more than 80,000 centenarians. Unlike Germany and many other developed countries, Japan's immigration policy is rather conservative, which makes Japan a homogenous society. By 2019, 2.8 million foreign residents lived in Japan, making up only 2% of the whole population. In comparison, approximately 12.7% of Germany's population are foreign residents. Due to the above factors, the Japanese population started to decline since 2011, which is rare for a large country during peaceful time. It is projected to drop from 126 million in 2020 to 88 million in 2065 (D'Ambrogio, 2020). Admittedly, deepening population aging with sub-replacement fertility has become a major threat to Japan's future economy.

Moreover, population aging is not only a severe crisis in the developed countries such as Germany and Japan, but also a rigorous challenge in emerging economies such as China and Africa.

In China, the population is currently experiencing a rapid, accelerated aging process due to several reasons such as improved medical standards, economic pressures, and decades-long family planning policies. According to National Bureau of Statistics, by the end of 2020, Chinese older adults aged 60 or over reached 264 million, accounting for 18.7% of the total population, which was equal to the population of Japan and Russia combined. In the meantime, population aged 65 or over reached 191 million, making up 13.5% of the total population (National Bureau of Statistics, 2021). As a result, China is about to enter "aged society" within five years. What is worse, it is anticipated to spend the shortest time (i.e., 33 years) to transfer from "aging society" to "super-aged society" compared to major developed countries in the world, which gives it much less preparation time to brace for social impacts caused by population aging. In addition, the imbalanced sex ratio at birth also exacerbated the situation. In-depth analysis regarding China will be conducted in later part of this thesis.

In Africa, the current situation does not look as bleak as other more developed regions. For example, according to the United Nations, the median age of the African population as a whole is only 19.7 years as of 2020. However, as the African population is projected to more than triple to a whopping 4.28 billion in 2100, the median age of the African population will increase to 34.9 by 2100, which is a significant increase compared to that in 2020. Accordingly, Africa's percentage of population aged 65 years or over will be 13.9% by then (United Nations, 2019), which will essentially meet the definition of aged society as well.

1.2 Overall consequences of population aging

Population aging has many consequences for society. First and foremost, it increases the chance of getting chronic noncommunicable diseases among older adults including but not limited to obesity, hyperglycemia, hypertriglyceridemia, hypertension (often referred to as "the deadly quartet") (Kaplan, 1989), cardiovascular diseases (CVDs), stroke, frailty, diabetes, osteoporosis, chronic respiratory diseases, dementia, Parkinson's disease, and deterioration of sensory organs. Suffering from these age-associated diseases puts substantial amount of physical and psychological stress to older patients and their families and friends.

Meanwhile, these diseases and syndromes not only mount burdens to individuals in society, but also sharply increase healthcare expenditures especially on long-term care (de Meijer et al., 2013). Take the European Union as an example: the health expenditures in the European Union is expected to increase by 350% by 2050 compared to an economic growth of 180% in the same time period (Espinoza, 2011). This increase will pose a major threat to the sustainability of public finances in aging societies around the world.

Furthermore, rapid population aging leads to labor shortages. It not only reduces the proportion of population participating in the labor market, but also leads to shortages specifically in the labor force taking care of a growing number of older adults. WHO estimated that there will be a shortage of more than 18 million health workers worldwide by 2030 (World Health Organization, 2016). Take Germany as an example: due to the impacts of population aging, Germany is already experiencing labor shortages in many sectors especially in the health sector, and the situation will only get worse over time. The consultancy firm PricewaterhouseCoopers AG predicted that there will be a shortage of nearly a million health workers (e.g., doctors, non-academic health workers, etc.) in Germany alone by 2030 (Ostwald et al., 2013). A similar trend can be observed in many other aging societies as well.

In addition, population aging also has an impact on economic growth. Researchers concluded that although population aging will not significantly hinder the economic growth of many developing countries, most OECD countries (i.e., developed countries) are likely to have slower pace of economic growth due to population aging (Bloom et al., 2011), which can further manifest in a series of consequences including slower increase in living standards, higher unemployment rate, and pressure on public services. Accordingly, behavioral changes and policy reforms are needed to mitigate the decline of economic growth rate.

The reasons for the phenomenon of population aging are manifold, two of which are the decreased human fertility rate and continuously increasing human life expectancy. In most countries, the total dependency ratio is increasing while the working-age population is shrinking, meaning that the pressures on the productive population are mounting. Researchers summarized three major challenges imposed by population aging: 1) the biological challenge which is to maintain good physical and mental ability in old age, 2) the social challenge which is to optimize policies related to aging, and 3) the cultural challenge which is to empower older adults to live with meaning and dignity (Sander et al., 2015).

The main purpose of this doctoral research, therefore, is to explore methodological and technological solutions as well as policy suggestions to mitigate the global challenges brought by population aging.

1.3 Situation of elderly care today

Society today is accelerating towards an aging society. However, the vast majority of older adults in the world live in "ordinary" homes rather than barrier-free homes designed specifically for them. Take the super-aged society Germany as an example, according to the report from the Federal Ministry of Transport and Digital Infrastructure in 2011, 93% of the older adults aged 65 or over in Germany live in “ordinary” homes, while only 5.2% of them live in elderly-friendly homes (Bundesinstitut für Bau- Stadt- und Raumforschung, 2011).

According to a 2020 statistical report by the German Construction Bank (Kreditanstalt für Wiederaufbau Bankgroup, KfW for short), there are three million households in Germany that require barrier-free elderly-friendly homes. By 2035, the number will rise to 3.7 million. However, the existing number of barrier-free dwellings are only 560,000, and there is a shortage of approximately 2.4 million elderly-friendly homes, and there will still be a deficit of two million elderly-friendly homes in 2035 (Leifels, 2020).

The difficulty of adopting aging-friendly homes now lies in the low willingness caused by high cost of renovation. The cost of only basic accessibility adaption has reached 19,200 euros, of which the average interior renovation costs 12,900 euros, and the barrier-free adaption costs 6,300 euros. The part that can be reimbursed is only a small percentage, and the impact of economic stimulus strategy for rental housing is insignificant (Zhu, 2021). Furthermore, statistics show that 82.7% of older adults are unwilling to renovate their houses, and the number rises to 92.4% for those over 80 years old (Bundesinstitut für Bau- Stadtund Raumforschung, 2011). Therefore, it is crucial to provide older adults with life assistance and rehabilitation equipment without the need to modify their existing homes.

Although technology has been used in elderly care for a long time, the elderly care industry in general still largely depends on human labor to carry out care tasks such as nursing, training, and physical therapy, whether it is at home, care home, or hospital. As discussed above, labor shortages accompanied by a barrier-free home deficit in aging society not only threaten the sustainability of society as a whole, but also is a major challenge in the elderly care industry. The COVID-19 pandemic only made the situation worse. To mitigate this shortage, technology needs to enable older adults to live more independently.

Taking care of the aging population with dignity is another great challenge facing the elderly care industry. Today, with advances in the medical science of the past decades, it is possible to enable people with severe illness to live without much pain. However, medical devices are still needed to support older adults to live in dignity in old age. These devices currently make the living environment resemble hospital rooms, which stigmatizes the users by reminding them of their poor health condition and leads to psychological struggles in later life. To solve this problem, technology shall be implemented in an unobtrusive way.

Therefore, a type of new technological system needs to be developed in a way that integrates the functionality into existing furniture and living environment, while being as unobtrusive as possible. A smooth implementation of the solution into the living environment increases user acceptance because additional benefits are added to the ambience of the apartment, but the appearance of the living environment remains familiar and cozy.

1.4 Embracing a paradigm shift in elderly care

In Thomas Kuhn’s world-renowned book The Structure of Scientific Revolutions, he challenged the notion of scientific progression at that time, which was the linear, incremental accumulation of knowledge. Based on the in-depth analysis of previous major scientific advances, he argued that science progressed not by incremental amendments to the existing knowledge base but by occasional revolutionary novel way of thinking (Kuhn, 1962). His revolutionary theory can be briefly summarized as several major steps of a scientific model based on the empirical analysis of the history of science (see Figure 1-1):

- Before the cycle of a scientific revolution cycle starts, there is a pre-science phase where several incomplete candidate theories coexist in the field and no specific paradigm is dominant. This phase only exists once before the cycle of scientific revolution.
- The first phase is normal science. In this phase, one of the candidate frameworks from the pre-science phase stands out to become the consensus and problems are solved accordingly within this dominant framework.
- The second phase is model drift. During this period, anomalies or problems that cannot be explained or solved within the paradigm begin to occur. While some anomalies can be resolved by adding amendments to the normal science, others are

difficult to explain or resolve within the old paradigm.

- The third phase is model crisis. This happens when the model of normal science continuously fails to explain or resolve anomalies. After significant efforts to resolve anomalies within the normal science fail, science may progress to the next phase.
- The fourth phase is scientific revolution where fundamentals of the model are shaken and a new paradigm is established. It is a revolution because the new model drastically differs from the previous one.
- The final phase is paradigm shift where a new paradigm becomes dominant in the field as normal science. All the problems in the field are solved within this paradigm until the next model revolution happens.

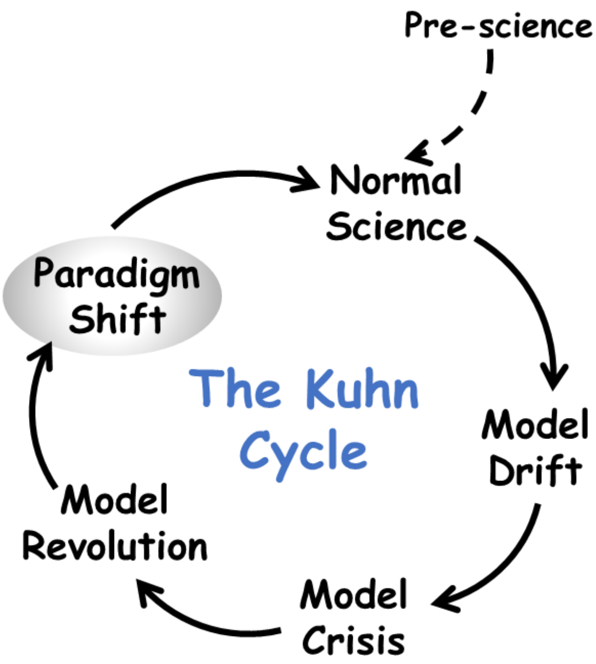


Figure 1-1: The Kuhn Cycle (based on the general concept of Kuhn, 1962)

Apart from the history of natural sciences, the influence of Kuhn's theory has expanded to other realms such as sociology, economics, and political science. Likewise, in the field of technology progress, from horse and carriage to automobiles, from tape cassette, CDs, and DVDs to online streaming services, from Zeppelins to airplanes, and from fossil fuels to renewable energy, similar patterns also can be observed: new paradigms made old technologies irrelevant if not completely obsolete.

As the level of population aging intensifies in many countries, the significance of gerontechnology became prominent in recent years. The idea dates back to several decades ago and the terminology of gerontechnology was officially proposed at the 1st International Congress on Gerontechnology, Eindhoven, Netherlands in 1991 (Bouma, 1992). It is a broad interdisciplinary domain that includes subjects such as gerontology, assistive technology (e.g., medical devices, home automation, companion robots, etc.), and inclusive design. Ever since its establishment, researchers and developers around the world continuously made contribution in this field.

Since more than a decade ago, a novel research area called ambient assisted living (AAL, sometimes also known as active assisted living) came into being. It can be considered as a branch of gerontechnology which focuses on providing people with technological assistance mainly in their natural living environment. The original ideas can be traced back to the 1980s. Sponsored by Japan Science Society anticipating future challenges of ageing society, one of the first concept was the life support system (LSS) for aging society developed by Mr. Thomas Bock in 1988, depicting visionary functions such as assisted dressing, smart home control, automated body turn-over, telemedicine, and emergency evacuation (see Figure 1-2). The concept was inspired by Mr. Bock's experience with the LSS for astronauts in space during his studies with space architecture professor Larry Bell from University of Houston, Texas, where he researched on the NASA Tech House built in Langley, Virgina, USA in 1979.

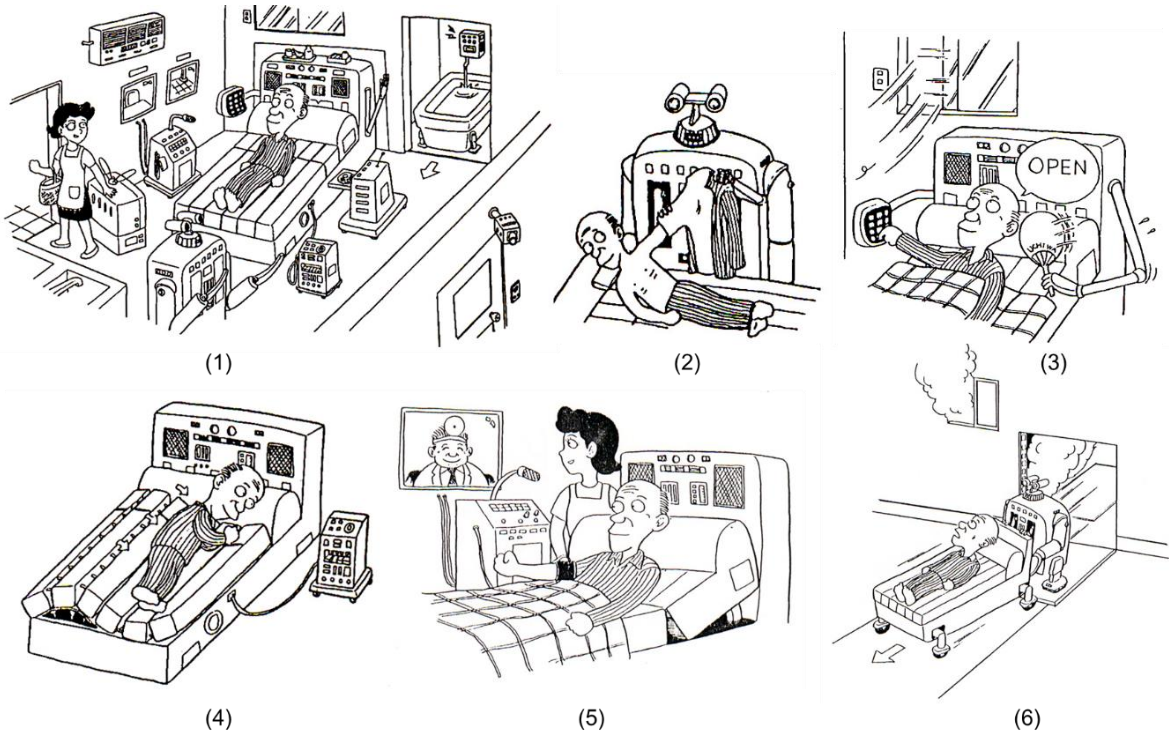


Figure 1-2: First concept of life support systems for aging society in Japan (source: T. Bock)

After the first concepts, many AAL systems and projects were developed over the years (which will be summarized in the next chapter). As the population aging crisis deepens as discussed in the beginning of this chapter, there will soon come a time when the current way of taking care of older adults is both socially and economically unsustainable due to the continuously increasing older population and severe labor shortages.

Therefore, it is foreseeable that a paradigm shift is likely to occur in the field of elderly care catalyzed by the population aging crisis (see Figure 1-3). In the future, caregivers and relatives of older adults can be liberated from the tedious daily tasks of caregiving and training in order to focus more on the psychological and emotional care, which are difficult to be substituted by technology such as robots in the foreseeable future.

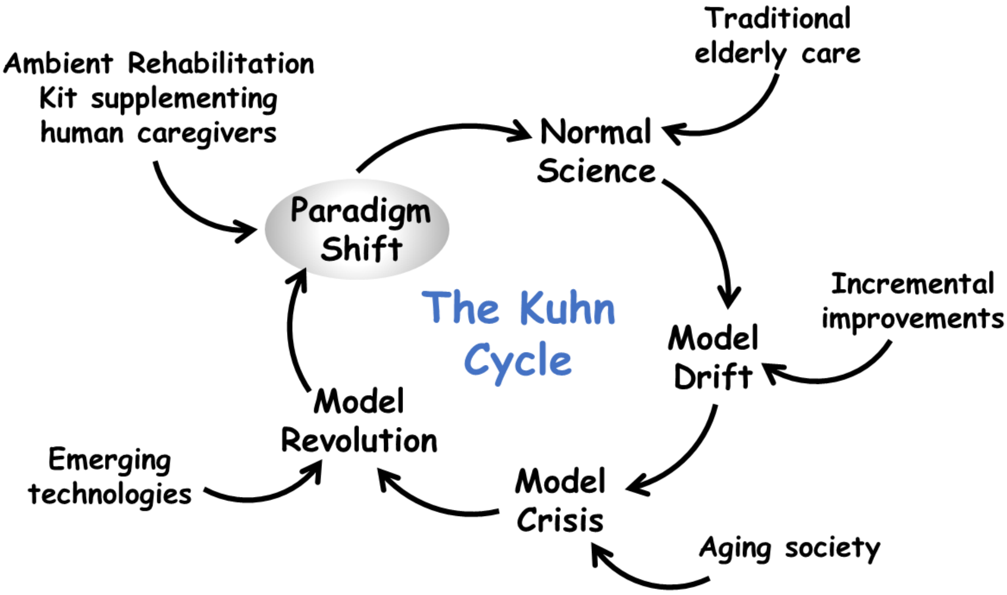


Figure 1-3: The Kuhn Cycle in the context of population aging

1.5 Research questions (RQs) and hypothesis

In an effort to mitigate the impact of rapid population aging, vigorous measures need to be taken in order to promote the activity and independence level of older adults. Consequently, more work shall be done to explore the technology to achieve this goal and the suitable methodology to develop it. Therefore, this thesis will focus on addressing the following main RQ:

- How efficient can the novel research field of Ambient Assisted Living help mitigate the crisis of population aging by increasing older adults' activity and independence level?

Accordingly, several sub-questions (SQ) of the main RQ can be raised further as follows:

1) What is the suitable methodology to develop such a system?
2) What are the main components and functions of the proposed system?
3) What is the financial performance of the proposed system?
4) How can the proposed system be introduced to markets outside Europe?
5) How can the proposed system be integrated into future smart cities?

Therefore, the main hypothesis of this doctoral thesis can be phrased as such: The Ambient Rehabilitation Kit developed with a systematic procedure model can increase older adults' activity and independence level, liberate the caregivers from tedious daily care and exercising tasks, and empower them to communicate on psychological and emotional level, eventually mitigating the impact of rapid population aging in an affordable and scalable manner.

Consequently, the rest of the thesis aims at proving the proposed hypothesis by addressing the RQ and its SQs.

1.6 Methodology: Continuous improvement in product development

To date, there are many types of methods for continuous product improvement which is also known as “kaizen (改善)”, meaning change for the better in Japanese (Imai, 1986) such as Kanban (Powell, 2018), Six Sigma (Antony, 2006), Look-Ask-Model-Discuss-Act (LAMDA) (Tortorella et al., 2015), and Plan-Do-Check-Adjust (PDCA), among which the PDCA method is arguably one of the most known and applied one worldwide (Realyvásquez-Vargas et al., 2018).

The PDCA method (also known as the Deming Cycle) is an iterative process management model for the continuous development and improvement of products. It is widely popular for its originality, simplicity, and practicality. Although its concept was first discussed by W. A. Shewhart in the late 1930s in his book Statistical Method from the Viewpoint of Quality Control (Johnson, 2002), it was widely known thanks to W. E. Deming when he taught seminars on quality, productivity, and statistical process control in Japan in the 1950s. He introduced the Deming Cycle to the Japanese to improve product quality and satisfy customers. It was further developed by the Japanese into a more general tool for product development called the PDCA model (Imai, 1986). Ever since its invention, the PDCA model has been widely used the Japanese industry as a systematic continuous problem-solving method, and was adopted by the Western industry in the early 1980s (Nilsson‐Witell et al., 2005). It soon evolved from a tool for product quality control at first to a method for improving the development process at the management level (Realyvásquez-Vargas et al., 2018).

The PDCA model consists of four phases: Plan, Do, Check, and Act. The phases are defined slightly differently in various literature but have the same purpose which is to continuously improve. Normally speaking, the Plan phase includes the identification and analyzation of the problem; the Do phase includes the development and implementation of the solution; the Check phase includes the evaluation of the result to check whether the goal is achieved; and the Act phase includes activities such as standardization and knowledge transfer (Johnson, 2002; Lodgaard et al., 2013).

Today, the PDCA model is considered not only a lean manufacturing tool, but a philosophy of continuous process improvement that is widely integrated in the corporate culture of continuous learning and knowledge generation (Realyvásquez-Vargas et al., 2018).

PDCA was also used in the development process of advanced building technology systems. For example, mainly based on the consultancy project on investigating the potential of implementing robotics and automation in the context of large-scale housing development for Hong Kong as well as several other research projects on developing construction robots, Linner et al. proposed a PDCA-based technology management system for the development of single-task construction robots (STCRs) based on the analysis of several exemplary research and development (R&D) projects in that field (Linner et al., 2019). The Ambient Rehabilitation Kit proposed in this thesis can be also considered as a special type of STCR system due to their common purpose of supplementing human labor with automation technology. Therefore, it is reasonable to apply this philosophy and method in the development process of ambient health promoting system as well.

One of the main goals of this doctoral research is to explore an effective and practical methodological framework for developing AAL technology. As shown in Figure 1-4, the basic structure of this methodology based on the Deming Cycle has four layers. Flexible starting point and continuous improvement are important for developing gerontechnology products because it is difficult to immediately specify the requirements, system architecture, work process, and business strategy. Therefore, an iterative and cyclic approach is appropriate. The primary goal of the proposed procedure model is the continuous evolution of the system architecture and the technical readiness levels (TRLs) of its subsystems (Layer 1). The core elements around the center are the four primary development phases based on the V-Model, which are requirements engineering, development, performance evaluation, and implementation (Layer 2). Guided by the Deming Cycle (Layer 3), each phase consists of various modular steps belonging to this phase such as specific activities and tasks (Layer 4). The non-inclusive activities and tasks listed in Layer 4 essentially constitute a modular toolkit to complete the system development goal in several iterations, some of which can be repeated in different cycles to fit different contexts and regions.

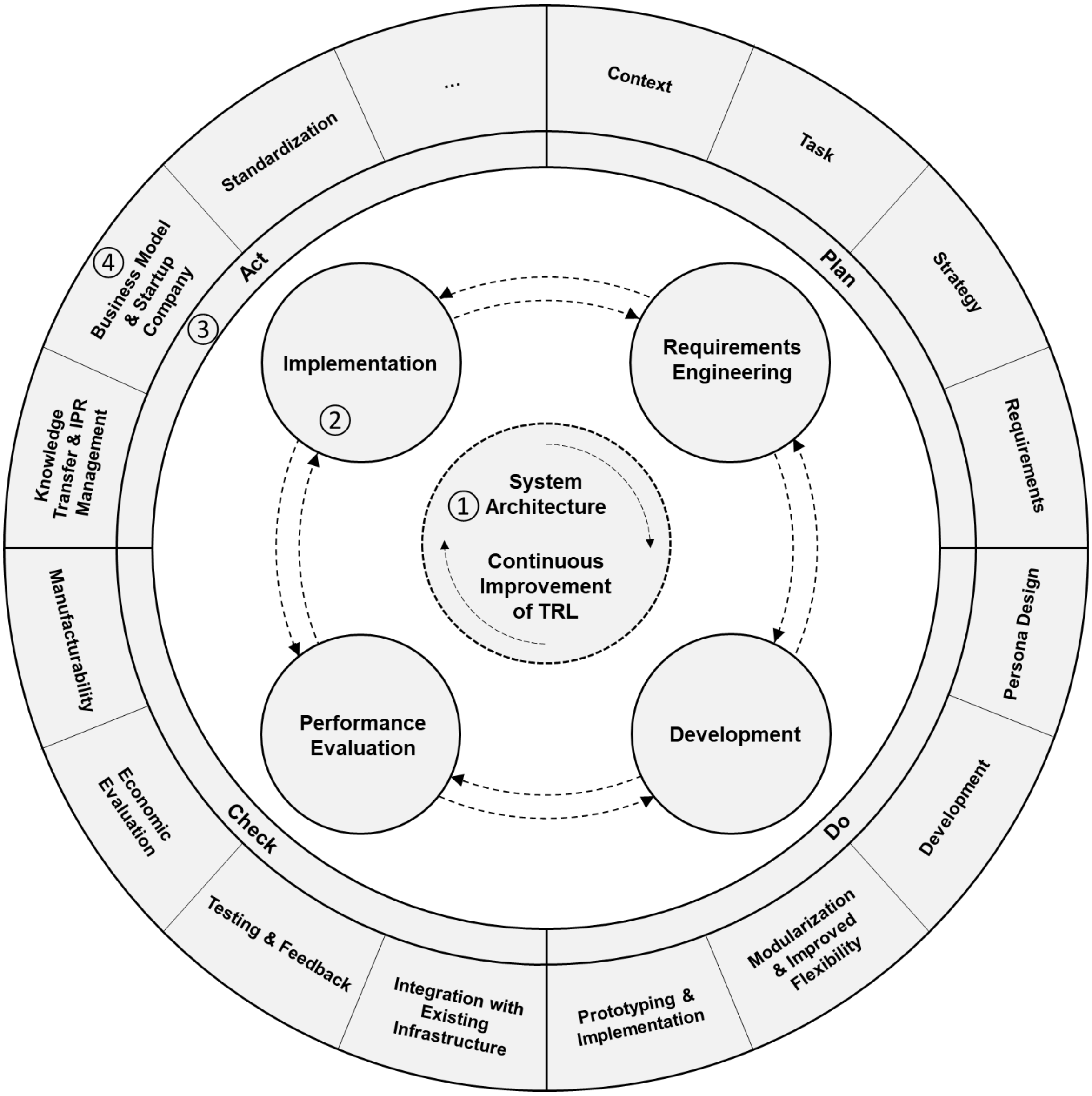


Figure 1-4: The procedure model for developing gerontechnology systems (model adapted from Linner et al., 2019)

As shown in Figure 1-5, multiple iterations of the procedure model will be adopted until the ultimate goal is achieved which is to successfully push the system to the market. This thesis mainly covers the first iteration of the procedure model for developing the Ambient Rehabilitation Kit as well as the “Plan” phase of the second iteration.

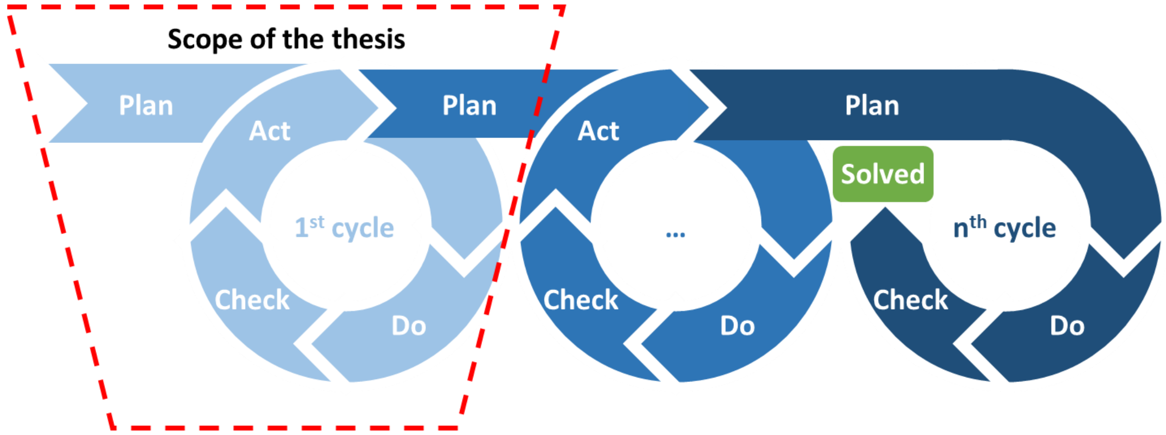


Figure 1-5: Iterations of the procedure model until the crisis is solved (figure redrawn and adapted from Christoph Roser at AllAboutLean.com, licensed under CC BY-SA 4.0, https://creativecommons.org/licenses/by-sa/4.0/)

1.7 Structure of the thesis

In order to systematically construct this doctoral thesis, it is divided into seven main chapters (see Figure 1-6). The first chapter includes background analysis, RQs and hypotheses, methodology, and structure description. The second chapter tackles the review of state-of-the-art technology and research work of the related field. The third chapter introduces the proposed solution and its prototypes in detail. The fourth chapter deals with the economic evaluation of the proposed systems. The fifth chapter focuses on an opinion survey conducted in China and a research roadmap for the Chinese market. The six chapter proposes a framework for developing future cities from a macro perspective based on advanced building theories and technologies. The last chapter summarizes the thesis and lays the foundation for future work.

The topic of each chapter narrows from Chapter 1 to Chapter 5 as it completes the first cycle of the PDCA model. Then the topic of Chapter 6 broadens again as the second PDCA iteration cycle starts. Throughout the past five years, the system components of this doctoral research were verified/validated in several research projects including but not limited to REACH, CIC Hong Kong Consultancy Project, LISA Habitec, HEPHAESTUS, and A^{2}L-Mobilius.

In particular, the REACH project has received funding from European Union's Horizon 2020 research and innovation programme under grant agreement No 690425. The CIC Consultancy Project was commissioned by the Construction Industry Council Hong Kong. The LISA Habitec project is financed by the Autonomous Province Bozen, Italy. The HEPHAESTUS project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 732513. This A^{2}L-Mobilius project is partly funded by the German Federal Ministry of Education and Research (Project: AL^{2}MOBILIUS; Grant Number: GERF-IB-033 Almobilius_01DH14003).

The structure of the doctoral research is illustrated below in Figure 1-6.

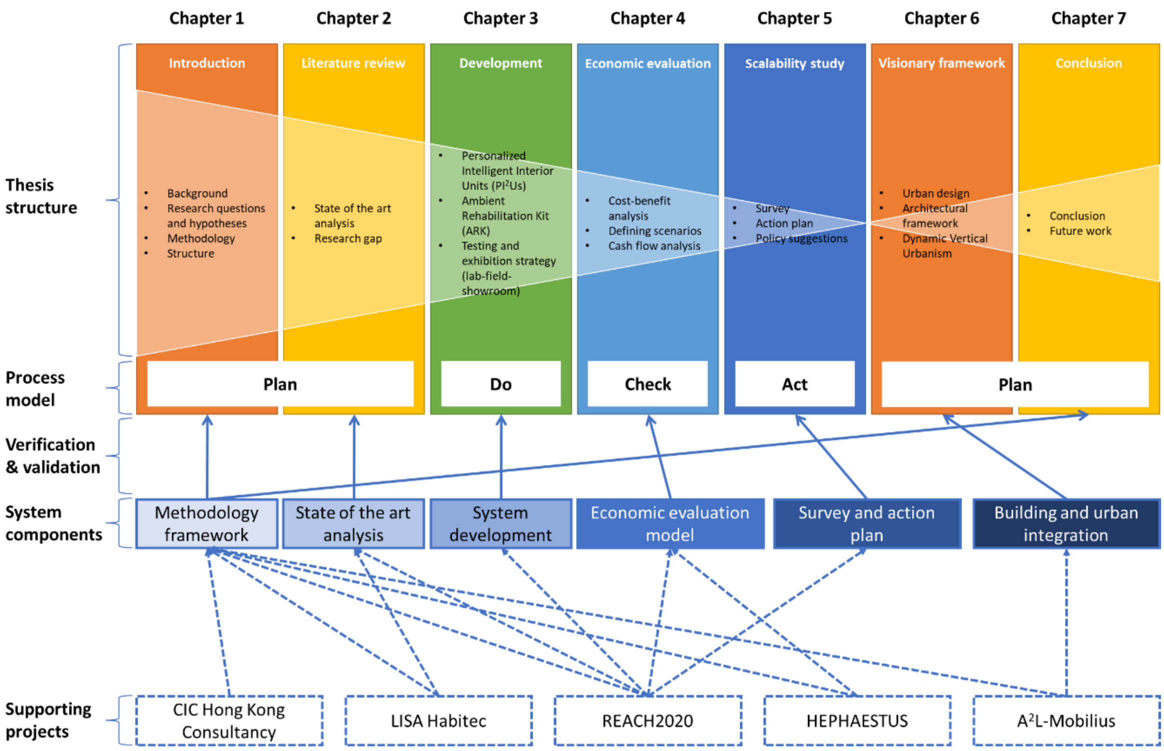


Figure 1-6: Structure of the thesis

Furthermore, as indicated in Figure 1-6, this doctoral thesis not only is a thesis on the development of the Ambient Rehabilitation Kit, but also can be used by researchers and developers as a handbook on how to develop an automated technological solution for healthcare industry and beyond in a systematic manner. In the following chapters, the state-of-the-art analysis, development of the proposed system, cost-benefit analysis, scalability study outside Europe, and a visionary future city framework will be elaborated respectively.

2 From fantasy films to future reality: A brief review of AAL technology for aging society (plan)

“I can't define a robot, but I know one when I see one.”

Joseph Engelberger[3]

To develop any technology, understanding the background and state of the art is a crucial first step. This chapter first analyzes the facts and characteristics of aging and its related diseases. It further discusses the change of people’s attitude towards assistive technologies such as robotics and AI the in the perspective of sci-fi movies. Based on the understanding of aging-associated diseases and human’s attitude towards advanced technologies, this chapter analyzes the challenges and shortcomings of the state-of-the-art AAL systems and summarize the main objectives of the system to be developed accordingly.

2.1 Aging and the related diseases

In order to better develop technology for older adults, their physiological characteristics and common diseases need to be understood. Therefore, in this section, common facts of aging and aging-associated diseases will be discussed.

2.1.1 Aging

Nobody likes it, but everyone does it: getting old. The biological process of aging started simultaneously with the inception of life some 3.5 billion years ago. It is characterized as the accumulation of various harmful changes in cells, tissues, and organs as the age increases, adding to the risk of illness and eventually death (Harman, 2001).

Observing the appearance of human body, aging can be easily recognized: The hair grows grey, the back becomes curved, the height shrinks, the skin turns loose, and the wrinkles on the face increase. Observing at the level of cellular and molecular biology, however, aging is much more complicated. Hayflick first discovered through lab observation the Hayflick Limit in the 1960s, which suggested that normal can only replicate for a certain number of times (i.e., 40-60) (Shay and Wright, 2000). Furthermore, scientists summarized nine hallmarks of aging, namely “genomic instability, telomere attrition, epigenetic alterations, loss of proteostasis, deregulated nutrient sensing, mitochondrial dysfunction, cellular senescence, stem cell exhaustion, and altered intercellular communication” (López-Otín et al., 2013). Aging is not a disease per se, but its biological hallmarks will lead to specific aging-associated diseases, which will be introduced in the next sections.

[3] Joseph Engelberger (1925-2015): American physicist, engineer, and entrepreneur.

In the long history of humankind, although life expectancy at birth has substantially increased especially in the past century, the limit of human life span has stayed the same at approximately 125 years. To date, the way to slow down the human aging process is still unknown (Hayflick, 2000). Given that the aging process is inevitable, how to age healthily has become an important topic. Rowe & Kahn summarized three key cornerstones of successful aging: 1) reducing risk factors for disease and disability, 2) good cognitive and physical function, and 3) active engagement with life (Rowe and Kahn, 1997). These three components also coincide with the goal of this doctoral research.

2.1.2 Metabolic syndrome: the deadly quartet and its consequences

As people age, the chance of acquiring metabolic syndrome greatly increases. Metabolic syndrome is an umbrella term for several metabolic conditions including abdominal obesity (i.e., central obesity or upper body obesity), hyperglycemia (i.e., high blood sugar or glucose intolerance), hypertension (i.e., high blood pressure), and hypertriglyceridemia. Kaplan for the first time compared central obesity, hyperglycemia, hypertriglyceridemia, and hypertension as the deadly quartet (Kaplan, 1989). In his groundbreaking 1989 paper, he revealed the pathogenic interrelationship between the deadly quartet, namely abdominal obesity links to hyperglycemia, hypertension, and hypertriglyceridemia, with hyperinsulinemia serving as the main intermediary (see Figure 2-1).

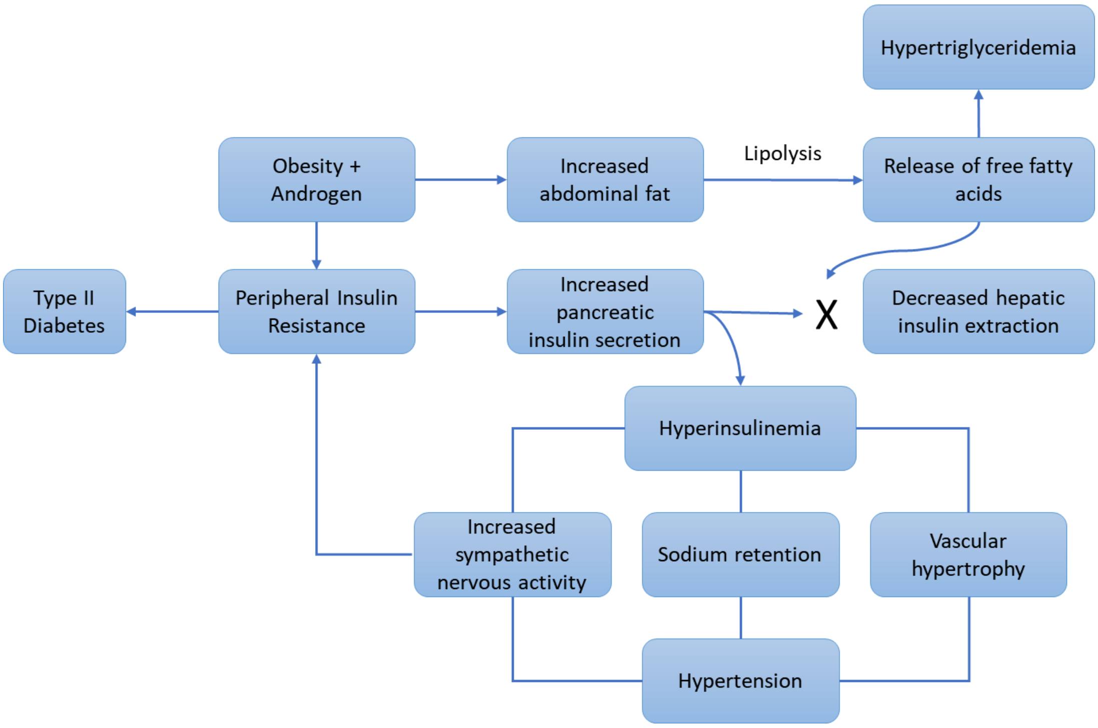


Figure 2-1: The interrelationship between metabolic syndromes (diagram adapted from Kaplan, 1989)

However, the real danger lies not in the metabolic syndrome itself, but in the fatal CVDs that the metabolic syndrome may cause, including but not limited to ischemic heart disease and stroke. If metabolic syndrome is not under control through medication, nutrition intervention, and physical exercise, it will cause other more fatal diseases. For example, chronic hypertension will damage the artery walls, further leading to occlusions. When the occlusion occurs in coronary arteries, it can cause coronary artery disease (also known as ischemic heart disease). Other risk factors for ischemic heart disease apart from metabolic syndrome include male gender, smoking, stress, and family history. Furthermore, when the occlusion occurs in cerebral arteries, it will mainly increase the risk for an ischemic stroke, which accounts for the vast majority of stroke events (Bock et al., 2019).

According to WHO, ischemic heart disease and stroke are the top two leading causes of death globally, killing 8.9 million and 6.2 million people in 2019 (accounting for 16.0% and 11.2% of total global deaths), and the numbers are on the rise (World Health Organization, 2020), see Table 2-1. As medical standards improve worldwide, the general trend is that the communicable causes of death are decreasing, while the noncommunicable causes of death (oftentimes related with aging) are increasing.

Table 2-1: Top 10 leading causes of death globally in 2019 (source: WHO Global Health Estimates)

No.	Cause of death	Amount in million	Share in %	Trend
1	Ischaemic heart disease	8.9	16.0%	Rising
2	Stroke	6.2	11.2%	Rising
3	Chronic obstructive pulmonary disease	3.2	5.8%	Rising
4	Lower respiratory infections	2.6	4.7%	Declining
5	Neonatal conditions	2.0	3.7%	Declining
6	Trachea, bronchus, and lung cancers cancer	1.8	3.2%	Rising
7	Dementia	1.6	3.0%	Rising
8	Diarrheic diseases	1.5	2.7%	Declining
9	Diabetes	1.5	2.7%	Rising
10	Kidney diseases	1.3	2.4%	Rising

Numerous studies have shown that physical activities have a beneficial impact on metabolic syndrome (Lakka and Laaksonen, 2007). Therefore, improving older adults' activity level will be an effective approach to rehabilitate from metabolic syndrome and its complications such as ischemic heart disease, stroke, and diabetes.

2.1.3 Diabetes

Diabetes mellitus (commonly known as diabetes) includes type 1 and type 2 diabetes. While type 1 diabetes is caused by absolute insulin deficiency because the pancreatic β cells are destroyed by the immune system, the pathogenesis of type 2 diabetes, on the other hand, is completely different. In regard to type 2 diabetes, the patient's pancreatic islets still produce insulin. However, the cells are oversaturated with sugar and become insensitive to insulin, causing an insulin resistance disorder, which can finally lead to diabetes. Both types of diabetes can cause severe complications such as vision loss, kidney failure, damage to the legs and feet, and a high risk of cardiovascular disease. Many experts believe that the continuously increasing obesity rate caused by industrialized lifestyle leads to this epidemic (Marx, 2002). In 2019, diabetes killed 1.5 million people globally, and the number is rising as the world further industrializes. In highly developed countries, the situation is usually direr. For example, 34.1 million American adults (i.e., 13% of all US adults) had diabetes as of 2018 (Centers for Disease Control and Prevention, 2020).

While type 1 diabetes an unpreventable autoimmune disease mostly affecting younger people, the vast majority diabetic individuals (approx. 90%) have type 2 diabetes, which is a reversable condition for many people through behavior change (Bock et al., 2019). Along with diet change (e.g., reducing sugar consumption) and medication (e.g., metformin), increasing physical activity level is essential for managing diabetes and lowering the risk of related complications (Hamasaki, 2016).

2.1.4 Chronic obstructive pulmonary disease (COPD)

COPD is a type of chronic respiratory disease that is characterized by "progressive airflow obstruction that is only partly reversible, inflammation in the airways, and systemic effects or comorbidities" (Decramer et al., 2012). The main risk factor is smoking, although other risk factors also have been identified such as aging, air pollution, occupational hazards, male gender, and genetic factors (Mannino and Buist, 2007). It is the third leading cause of death worldwide, resulting 3.2 million deaths globally in 2019 (see Table 2-1).

In addition to smoking cessation and medical treatment, physical exercise can be an effective rehabilitation method for COPD patients. Back in 1895, Dr. Denison from University of Denver published a book titled "Exercise and Food for Pulmonary Invalids", in which he proposed for the first time to relieve COPD through physical exercise. To date, many studies indicated that physical exercise being part of integral pulmonary rehabilitation program can greatly improve the quality of life of patients with COPD through reducing symptoms, improving fitness, and relieving anxiety and depression (Spruit et al., 2016).

2.1.5 Osteoporosis

Osteoporosis is a health condition characterized by decreased bone density and deteriorated bone microarchitecture that can increase the risk of fragility fractures (Rachner et al., 2011). It also leads to a typical body shape change, namely kyphosis and height loss, caused by compressed vertebral bones. Osteoporosis itself may not look so deadly, but the related fragility fractures caused by falls are highly fatal. For example, the mortality rate in an older individual with hip fracture is nearly 20%. The direct pathogenesis of primary osteoporosis is largely unknown, but the risk factors include but are not limited to aging, malnutrition, low body mass index (BMI), smoking, alcohol consumption, physical inactivity, sex hormone deficiency, specific type of cancers, and drug use, and genetic factors (Christodoulou and Cooper, 2003).

The economic burden of osteoporosis is enormous. In the European Union (EU27) alone, the annual costs of osteoporotic fracture prevention and treatment was €37 billion as of 2010, and the costs are estimated to increase by 25% by 2025 (Hernlund et al., 2013). Measures to reverse osteoporosis include increasing calcium and vitamin D intake, quitting smoking, reducing alcohol consumption, and increasing physical activity, and medical treatment. Furthermore, preventing falls is critical for older adults suffering from osteoporosis due to an increased risk of fracture (Christodoulou and Cooper, 2003).

2.1.6 Dementia

The word “dementia” derives from Latin, which literally means “without mind”. According to WHO, dementia is “a syndrome in which there is deterioration in memory, thinking, behaviour and the ability to perform everyday activities” (World Health Organization, 2019). A large number of the world population is suffering from dementia, and Alzheimer’s disease is estimated to contribute to 60-70% of the total dementia cases. By 2015, roughly 47 million people suffer from dementia and the number is expected to reach 132 million in 2050 (World Health Organization, 2017). In Germany, for example, more than 1.6 million people were affected by dementia (Michalowsky et al., 2017). The dementia epidemic has a significant negative impact in terms of physical, psychological, economic, and social aspects, not only on the patients themselves, but also on their caregivers, families, and society. Because there is no effective medication currently available to cure dementia or reverse its progression (Perneczky, 2019), assistive technology can be a solution to mitigate the impact of dementia and increase the independence of people living with dementia.

2.1.7 Parkinson’s disease

Being the second most common neurodegenerative disorder, Parkinson’s disease (or simply Parkinson’s) is a progressive nervous system disorder specially affecting the elderly community. It affects about six million people around the world, and the number of patients is expected to double over the next generation (de Lau and Breteler, 2006; Poewe et al., 2020). Parkinson’s usually leads to tremors, rigidity, disability, long-term care (LTC), deteriorated quality of life, and eventually premature death, which put increasing burdens on the caregivers and affect the patients and their families both financially and psychologically (Heinzel et al., 2018). Currently, although there are drugs to mitigate the symptoms of Parkinson’s, there is no effective cure for it. Therefore, the activities of daily living (ADLs) of people living with Parkinson’s need to be assisted by various means.

2.1.8 Deterioration of sensory organs

Another common problem for aging population is the deterioration of sensory organs including eyes and ears. Common diseases of sensory organ deterioration include cataract, glaucoma, macular degeneration, age-related hearing loss (Bock et al., 2019), and age-related olfactory dysfunction (Attems et al., 2015). Although sensory organ deterioration is not as life-threatening as other diseases mentioned above, it can bring great physical and psychological burden to older adults, and substantially reduce their quality of life. To make matters worse, sensory dysfunctions often links to severe neuropsychological diseases such as cognitive decline and depression (Rong et al., 2020; Wongrakpanich et al., 2016). Therefore, strengthening older adults' social interaction with other individuals is important to mitigate the impact of sensory organ deterioration.

2.1.9 Coronavirus disease 2019 (COVID-19)

COVID-19 is a highly infectious respiratory disease caused by severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) (Yuki et al., 2020). After first identified in December 2019, it soon became a global pandemic that has infected more than 200 million individuals and claimed over four million lives worldwide, and the number continues to rise as of December 2021. To date, several vaccines against COVID-19 have been rolled out. However, challenges remain due to slow and unequal vaccine distribution, and rapid virus mutation. In fact, many experts worry that it is likely to become seasonal epidemic like influenza (Hunter, 2020). Therefore, it can be concluded that COVID-19 pandemic has already changed the way human beings live profoundly, and some changes will likely remain permanently (Nicola et al., 2020; Yang et al., 2020).

COVID-19 is not an aging-associated disease per se, but is disproportionally more fatal to older individuals (Marois et al., 2020). As a result, preventing the most vulnerable group from contracting the coronavirus is critical in reducing the number of deaths. Therefore, increasing the independence level of older adults can help them better survive the pandemic.

2.2 Human's attitude towards robots, automation, and AI from the perspective of sci-fi movies: Fear and hope coexist

Motion pictures have become the mainstream entertainment method for humankind for more than 100 years. They reflect and at the same time can affect the beliefs, values and attitudes of people in each era (Ashworth, 2019). Science fictions as well as sci-fi films play an important role in human culture. New scientific advances inspired sci-fi writers, whose works in turn influenced scientists and engineers in their research and inventions (Lorenčík et al., 2013). One of the most prominent examples is Three Laws of Robotics (Asimov, 1942), which despite its imperfections ignited the research field of robot ethics (McCauley, 2007).

Table 2-2 is a summary of basic information of 30 mainstream fictional films about robots, automation, and artificial intelligence (AI) in the past century. Through this brief chronology, it can be observed that from 1920s to 1960s, people generally had negative views such as fear and doubt about robots and artificial intelligence since almost no film portrayed robots and AI positively. From Metropolis (1927) to Der Herr der Welt (1934), then to 2001: A Space Odyssey (1968), sci-fi films in that period always tended to portray robots and AI as monstrous metal creatures keen to control human society. At the same time, in Mon Oncle (1958), one of the first films depicting home automation technology, the talented director J. Tati praised the traditional urban life with simple and natural interpersonal relationship, while unabashedly expressed his aversion to the cold, awkward modern residence Villa Arpel and the home automation technology inside (see Figure 2-2). This phenomenon was likely due to human's fear of the unknown as that kind of technology just started to emerge at that time.

Figure 2-2: A replica of Villa Arpel at the Cent Quatre in Paris. Photo by Hektor (unchanged and licensed under CC BY-SA 3.0, https://creativecommons.org/licenses/by-sa/3.0/)

The turning point occurred in the late 1970s when robots started to emerge with a positive image. For example, in Star Wars (1977) and its follow-ups, the two robots, C3P0 and R2-D2, impressed the audience deeply with their wise, brave, and humanized personalities. Most other sci-fi films about robots and AI from 1980s to early 2000s also portrayed them as positive characters, such as D.A.R.Y.L. (1985), Short Circuit (1986), Robocop (1987), Bicentennial Man (1999), and A.I. Artificial Intelligence (2001). During the that period, even films belonging to the same franchise changed their tune on robots: In the Terminator (1984), T-800 (played by A. Schwarzenegger) was portrayed as a cruel robot solider who travelled back from the future to assassinate the human resistance leader, whereas in the Terminator 2 and 3, the same robot became the savior of humanity.

After 2000, the pendulum swung again. Films about robots and AI became nuanced, reflective, and even contradictory. In this period, some films gave robots and AI a lovely image such as WALL·E (2008), and Robot and Frank (2012), while others depicted them as evil and repressive such as Ex Machina (2014), Upgrade (2018), and I Am Mother (2019). More often, however, the attitude towards robots and AI in films was complex and contradictory such as in I, Robot (2004) and Her (2013). This transition took place in an era where novel technologies such as robots and AI were rapidly developing and starting to place human labor on a large scale (de Vries et al., 2020).

The explosive growth of sci-fi films indicates that the adoption of robots, automation, and AI will be irreversible, but at the same time it will be full of risks. Therefore, when developing robot and AI technologies that are supposed to serve human, the engineer community must be highly cautious about the ethics and regulations of technology to prevent it from backfiring on human. Accordingly, a scientific methodology for developing such systems is also needed to increase the acceptance and ensure the success of such systems.

Table 2-2: Major sci-fi films about robots, automation, and AI in the past century (source: www.imdb.com)

Name	Country	Year	Director	Main character	Overall attitude towards robots and AI		
					Negative/ fear	Neutral/ contradictory	Positive/ hope
Metropolis	Germany	1927	Fritz Lang	Robot	■		
Der Herr der Welt	Germany	1934	Harry Piel	Robot	■		
The Mechanical Monsters	USA	1941	Dave Fleischer	Robot	■		
Mon Oncle	France	1958	Jacques Tati	Automation	■		
Alphaville	France	1965	Jean-Luc Godard	AI	■		
2001: A Space Odyssey	USA	1968	Stanley Kubrick	AI	■		
Westworld	USA	1973	Michael Crichton	Robot	■		
Star Wars	USA	1977	George Lucas	Robot			■
The Terminator	USA	1984	James Cameron	Robot	■		
D.A.R.Y.L.	USA	1985	Simon Wincer	Robot			■
Short Circuit	USA	1986	John Badham	Robot			■
Robocop	USA	1987	Paul Verhoeven	Cyborg			■
Edward Scissorhands	USA	1990	Tim Burton	Robot			■
Terminator 2: Judgment Day	USA	1991	James Cameron	Robot		■	
The Matrix	USA	1999	Lana Wachowski & Lilly Wachowski	AI	■		
Bicentennial Man	USA	1999	Chris Columbus	Robot			■
A.I. Artificial Intelligence	USA	2001	Steven Spielberg	Robot			■
Terminator 3: Rise	USA	2003	Jonathan	Robot		■	

of the Machines			Mostow				
I, Robot	USA	2004	Alex Proyas	Robot			
Transformers	USA	2007	Michael Bay	Robot			
WALL·E	USA	2008	Andrew Stanton	Robot			
Surrogates	USA	2009	Jonathan Mostow	Robot			
Real Steel	USA	2011	Shawn Levy	Robot			
Robot and Frank	USA	2012	Jake Schreier	Robot			
Her	USA	2013	Spike Jonze	AI			
Autómata	Spain	2014	Gabe Ibáñez	Robot			
Ex Machina	UK	2014	Alex Garland	Robot			
Chappie	USA	2015	Neill Blomkamp	Robot			
Upgrade	USA	2018	Leigh Whannell	AI			
I Am Mother	Australia	2019	Grant Sputore	Robot			

2.3 State-of-the-art AAL systems and shortcomings

In recent years, due to the pressure from social challenges such as aging societies, limited resources, and a continuously increasing demand for productivity and efficiency, the topics of AAL smart furniture and smart homes are becoming more and more popular.

It has been demonstrated that smart furniture to a limited extent can integrate sensory and intervention functionality (Linner et al., 2015) as well as elements of the building technology. A particular focus in that context was given to the development of smart chairs (Erdt et al., 2012), smart bathroom furniture (Manoel et al., 2017), smart kitchens (Beetz et al., 2008; Yan et al., 2007), smart home workspaces (Linner et al., 2016) and smart beds (Spillman et al., 2004; Van der Loos et al., 2003). An obvious shortcoming of the aforementioned furniture schemes is that the majority are stand-alone devices that are not integrated into a larger framework (i.e., they are not connected to other components and do not form part of a bigger analytical scheme that makes use of the large quantity of information that can possibly be produced through such processes) or are incapable of monitoring the entire area where they are positioned. A further weakness is the lack of modularity and the limited amount of functionality the systems provide.

There are several intelligent sensing solutions proposed, such as the Aware Home (Kidd et al., 1999) and the RoboticRoom (Sato et al., 2004). All of them are ambitious proposals of implementation of smart environments (i.e., buildings or rooms that are equipped with sensing functions for sensing of a large amount of data, intervention modules and robotic functionality). All aforementioned examples use sensor networks for intelligent robots

(Murakami et al., 2008) and achieved positive results. These examples are aspiring, but at the same time are extremely specialized and, in particular, lack the capacity to integrate such environments into a regular home or home care setting due to their high cost and the need for fundamental changes to the environmental architecture. Also, due to the lack of considering modularity, the installation process of these systems is complex and time consuming. Furthermore, given that the systems are not highly specialized and unified, they operate only based on their own capabilities without complementing each other in functionality and often monitor similar aspects twice or more, leading to high redundancy and cost.

The transformation of buildings into smart homes (Hsu, 2012; Intille et al., 2006), assistive environments for senior citizens (Wichert and Mand, 2017), or robotic environments (Kurazume et al., 2017; Pyo et al., 2015; Sugano and Shirai, 2006; Williams and Nayak, 1996) are currently in the focus of the research and development of both academia and industry. However, many attempts have been made to embed intrusive sensory and motivation functions into the built environment to support the monitoring and care for healthier and more independent older adults' living (Intille, 2004, 2002; Pyo et al., 2014; Sakamura, 1996; Sato et al., 2004). In addition, despite the opportunities these technologies provide, their real-world deployment oftentimes requires an intrusion into the physical building and to a large extent is hindered by their complexity, time and cost associated with equipping buildings with such functionality.

Therefore, a novel approach is needed to address the abovementioned issues such as a lack of integration, insufficient modularity, complicated installation process, intrusive monitoring, and fundamental changes to the existing environment.

2.4 Latest practices of AAL research projects

In order to address the abovementioned shortcomings of the state-of-the-art gerontechnology, a series of research projects carried out by the Chair of Building Realization and Robotics at Technical University of Munich (TUM) tackling various aspects of AAL are reviewed as follows.

2.4.1 GEWOS

GEWOS stands for "Gesund Wohnen mit Stil" (or in English "Healthy Living with Style"). It was funded by Federal Ministry of Education and Research of Germany (BMBF) with a total budget of €3.6 million. The project began in 2010 and ended in 2013. The main objective of the project was to develop a mechatronic chair that is equipped with invisible but sophisticated sensor technology that measures a multitude of user vital signs. The following sensor systems were embedded: electrocardiography (ECG) module, saturation of peripheral oxygen (SPO2) module, module for weight measurement, and module for measuring activity. By encouraging movement and supporting further exercising methods, this system serves as a health promoter, embedded in the physical and emotional surrounding of the user. Hence, the GEWOS sensor chair can be considered as an integral socio-technical system that comprises an innovative chair with sensors, an internet-based platform, a user-friendly interface, and interaction functions with matching services (Linner and Schulz, 2015).

The GEWOS project was arguably one of the first attempts to integrate state-of-the-art sensing and training functions into everyday furniture. The project was apparently a step towards the right direction and the concept is worthy of further exploration (see Figure 2-3).

Figure 2-3: The GEWOS mechatronic chair with sensing and training features (Photo: T. Bock)

2.4.2 PASSAge

PASSAge is the project acronym of "Personalized Mobility, Assistance and Service Systems in an Aging Society". It was funded by BMBF with a total budget of €3.9 million. The project started in 2012 and ended in 2015. The project addresses the mobility issues in aging society by developing a modular and personalized mobility system that can be integrated into the individual surrounding of older adults, improving the quality of everyday life by encouraging autonomous mobility, as well as supporting health, safety, and comfort. The intention was to identify, develop and validate robotic-based concepts for in-home mobility, logistics, and transfer to support the older adults within their living environment. Controlled by a master PC, adaptable, customizable, and user-friendly add-on modules are built upon existing technologies and innovative mobility components, including an automatic door opening system, a robot-driven rollator, and a StairWalker integrating a transport platform (Bock et al., 2015) (see Figure 2-4).

Figure 2-4: The StairWalker integrating a platform where the user put the rollator or grocery

2.4.3 USA²

USA² stands for "Ubiquitäres und selbstbestimmtes Arbeiten im Alter" (or in English "Ubiquitous and Self-determined Work in Old Age"). It was funded by BMBF with a total budget of 300,000€. Nowadays, older adults can be considered as an important labor force for future industrial development in Germany, in the context of design and production of personalized value-added products/services that demand skilled and experienced labor. In the context of this project, a mini-factory-type workspace resembling a cockpit was developed that integrates novel manufacturing technologies such as telepresence, cooperative robotics, 3D printing, and cloud manufacturing (Linner et al., 2016) (see Figure 2-5).

Figure 2-5: Prototype of USA² cloud manufacturing station

2.4.4 LISA

LISA stands for "Living Independently in Südtirol/Alto Adige". It was sponsored by the Italian government and the city of Bolzano with a total budget of €1.2 million. In the LISA project, the main objective was to implement a novel robotic service wall to support older adults' ADLs. The system followed a modular approach in which all system elements features "plug-and-play" characteristics. This type of approach enables an efficient system, which can be deployed and rearranged into various configurations and can be easily installed in any residence without requiring specific space dimensions. Through LISA's mechatronic service wall, an ambient intelligence environment can be established within a house or apartment. A variety of services can be tackled by the system, leading to a higher level of quality in ADLs as well as a higher level of safety because the system can contact emergency services. After an early design phase, two 1:1 prototypes were manufactured and evaluated by the research team using an old age simulation suit. Finally, the mechatronic service wall was installed in a real house for three months and evaluated by potential older users (Georgoulas et al., 2015).

2.4.5 LISA Habitec

The project LISA Habitec (short for Living independently in Südtirol Alto-Adige through an Integration of Habitat, Assistance, Bits and Technology) was the follow-up project of LISA. It aimed at installing Robotic Micro-Rooms (RMRs) within the entire apartment, thus expanding the system to further Life Centers (e.g., entrance, food, body care, relax, etc.). The project focused on the design, development and integration of assistive functions into building components (e.g., ceiling, wall, etc.) to enable independent living through structured environments (see Figure 2-6). Specifically, vital signs measurements such as body temperature and ECG, and position sensing like fall detection are unobtrusively implemented into the terminals, in order not to stigmatize the user. The combination of various assistive technologies encourages the user to be more independent. Through the modular approach, the terminals can be personalized according to user's financial situation, as well as the actual user's needs (Güttler et al., 2017).

The LISA Habitec project was a step in the right direction to create an assisted living environment for older adults. However, there were still several shortcomings in the two LISA projects. First of all, the system provided mainly assistive functions, rather than training and rehabilitation functions. Furthermore, the system enabled fast installation and disassembly, but lacked mobility and transferability functions for older adults. In addition, some modules such as the entrance and bath module still require significant modification to the existing living environment, which can potentially hinder the adoption given that renovation nowadays is extremely expensive.

Figure 2-6: Various Life Centers in Lisa Habitec (image: adapted from MM Design with permission from MM Design)

2.4.6 BaltSe@nior

The BaltSe@nior project improves the safety and quality of life of older adults and creates new business opportunities for the Baltic Sea Region by innovative design processes, user-oriented development, and smart furniture solutions. The goal is to organically combine the traditional furniture industry and state-of-the-art ICT solutions. The results of joint innovation camps and design workshops are several prototypes of furniture employing innovative ICT solutions, such as a magic mirror displaying personalized messages, a ReAbleChair collecting data on sit-to-stand movements, a smart chair supporting physical rehabilitation, and an assistive mobile robot with the fall detection and stand-up support function (Langosch et al., 2019) (see Figure 2-7).

Although it is highly important to detect fall incident in order to carry out support or rescue, oftentimes the fatal damage has already been done when falls take place, especially for fragile older adults suffering from osteoporosis. Thus, fall prevention also needs to be addressed in future research activities.

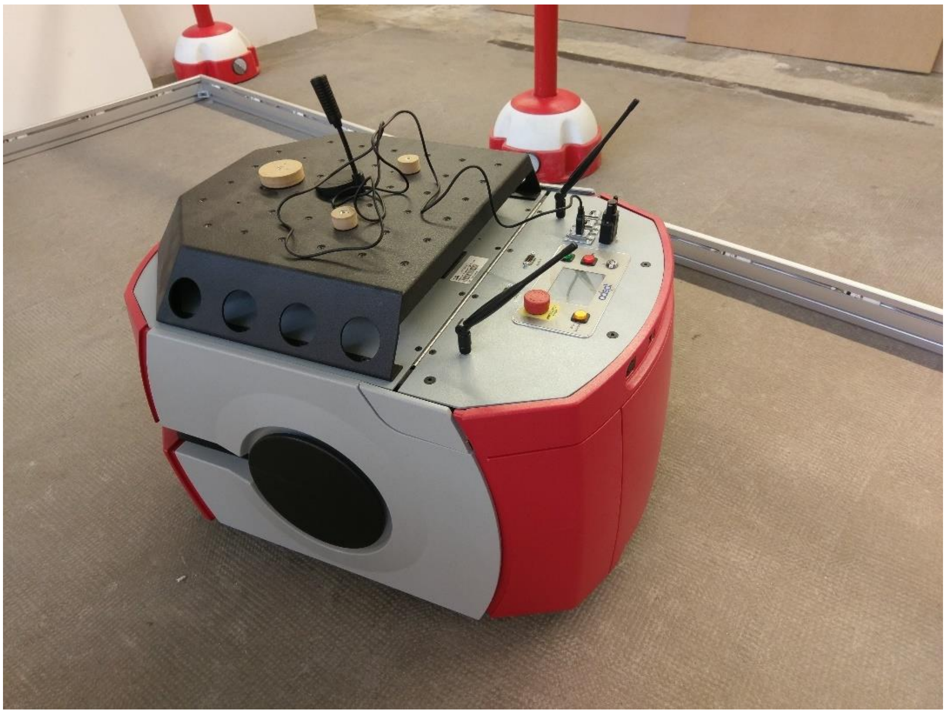


Figure 2-7: The assistive mobile robot in the infrared fall detection field

2.4.7 A²L-Mobilius

Nowadays, approximately 70% of Greater Cairo's 20 million inhabitants are living in urban informal settlements, and the number is expected to continuously increase. These informal settlements suffer from various issues such as overpopulation, high unemployment rate, land shortage, poor living conditions, inadequate infrastructures, and environmental pressures. The research project A²L-Mobilius is partly funded by BMBF with a total budget of 150,000 € (Grant Number: GERF-IB-033 Almobilius_01DH14003). The goal of this research is to explore an integrated approach to improve the living condition of local residents as well as to revitalize the local communities. By investigating the context of informal settlements in Cairo, an Affordable and Adaptable Building System (A²BS) based on open building concepts is proposed, which can be easily prefabricated and assembled by unskilled labor. Meanwhile, Decentralized Processing Units (DPUs) tailored to the building system are introduced to enhance three main aspects of life (working, energy, and mobility). Finally, a simulation of a regenerated house based on the selected case study building is presented, which integrates A²BS and various DPUs (see Figure 2-8). Additionally, an appropriate business model for the future prosperity of the local communities is discussed in the context of Decentralized Industrial Village (DIV) (Ilhan et al., 2018).

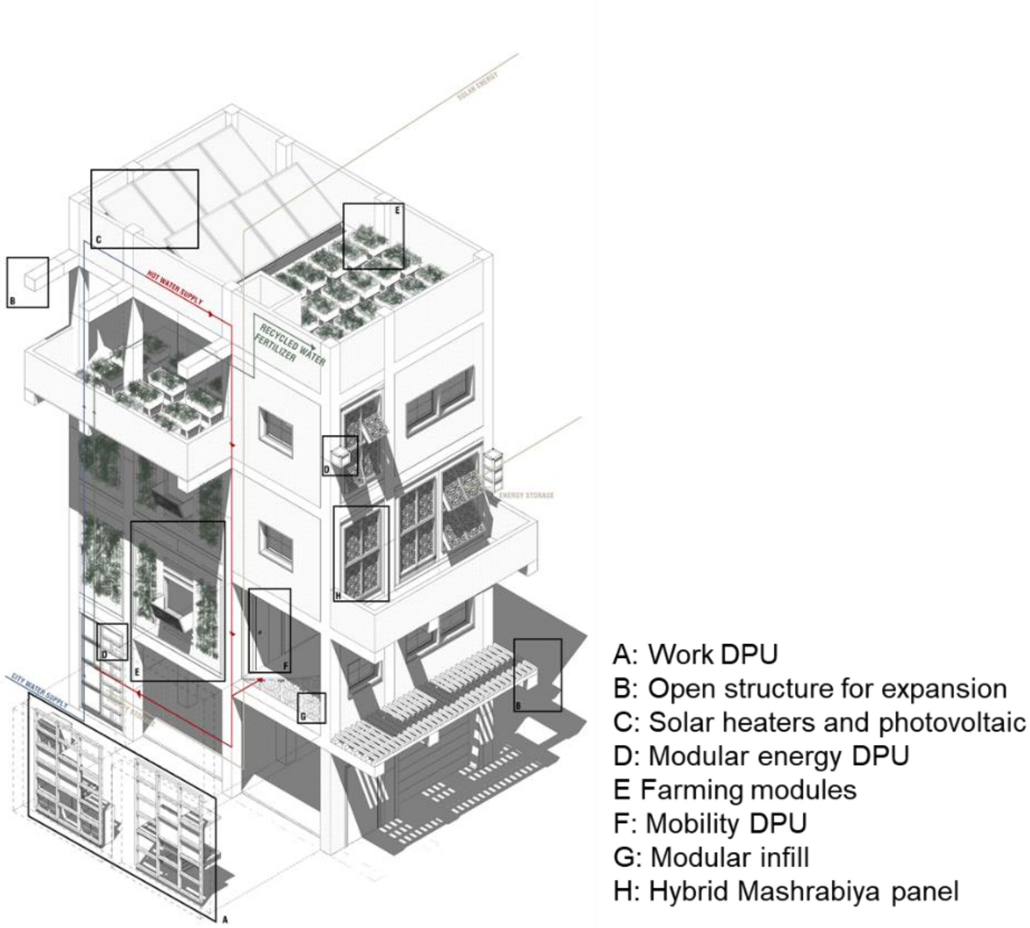


Figure 2-8: Simulation of a regenerated house based on the selected case study building integrating A²BS and various DPUs

In conclusion, this research will be a step forward to improve the living conditions of informal settlements in Cairo and worldwide (Hu et al., 2017). Based on the proposed system in A²L-Mobilius, further framework for developing future smart city beyond the informal settlements in Egypt needs to be developed.

2.5 Technological objectives based on the research gap

Admittedly, aging-related health issues need comprehensive interventions using various measures. Apart from medical treatment, assistive technology such as smart furniture can be a powerful tool to tackle the challenges posed by these issues (Bock, 2017). However, as analyzed above in this chapter, there are a variety of shortcomings still existing in the state-of-the-art assistive technology as well as latest AAL research projects, including a lack of modularity, compatibility, flexibility, rehabilitation functionality, fall prevention, financial feasibility, scalability outside Europe, and integration in the urban context (see Section 2.3 and Section 2.4).

Therefore, synthesized from the physiological features of older adults, the characteristics of aging-associated diseases, the shortcomings of the state-of-the-art-AAL technologies, as well as the preliminary analysis reports of the REACH project, it can be summarized that the assistive technological framework to be developed for older adults in the context of this doctoral research need to fulfill the following objectives.

(1) To develop modular, agile assistive technology that can be rapidly deployed the existing environment (see SQ2, Section 2.4.5, and REACH Deliverable D21 (Andersen et al., 2017)).

(2) To promote physical, mental, and social activities through communication and training with fun (see SQ2, Section 2.4.5, and REACH Deliverable D29 (Lu et al., 2017)).

(3) To assist the ADLs of older adults (see SQ2, Section 2.1, and REACH Deliverable D21 (Andersen et al., 2017)).

(4) To ensure safety and prevent falls when older adults use the system (see SQ2, Section 2.1.5, Section 2.4.6, and REACH Deliverable D21 (Andersen et al., 2017)).

(5) To increase the independence level of older adults (see SQ2, Section 2.1.6, Section 2.1.9, and REACH Deliverable D1 (Schäpers et al., 2016)).

(6) To ensure financially feasible rehabilitation solutions to mitigate the burdens on individuals and society brought by population aging (see SQ3, Section 2.3, and REACH Deliverable D33 (Lingegard et al., 2017)).

(7) To promote acceptance of gerontechnology products among older adults not only in Europe, but also other part of the world (see SQ4 and REACH Deliverable D30 (Ehrari et al., 2019)).

(8) To establish a bigger framework for the development of future smart city based on advanced building technologies (see SQ5 and Section 2.4.7).

After the objectives of this research are clear, the main content of the thesis will comprise the following parts. The preparatory work presented in Chapter 1 and Chapter 2 indicates that various novel technologies and solutions need to be developed, which will be introduced in the following chapters. Specifically, Objectives (1), (2), (3), (4), and (5) will be addressed in Chapter 3, Objective (6) will be elaborated in Chapter 4, Objective (7) will be tackled in Chapter 5, and Objective (8) will be explored in Chapter 6. Finally, Chapter 7 summarizes the whole thesis in accordance with the RQ and SQs, and lay the foundation for future research.

3 Ambient Rehabilitation Kit: An unobtrusive interdisciplinary approach to achieve demographic sustainability (Do-Check)[4]

"The fox knows many things, but the hedgehog knows one big thing."

Archilochus[5]

Aging society is a crisis that is experienced all around the globe, including developed countries such as Germany and Japan, and emerging economies such as China. According to the 2017 Revision of the World Population Prospects, the percentage of global older population (aged 60 or over) increased from 9% in 1994 to 13% in 2017 and is expected to reach 21% by 2050 (United Nations, 2017). This phenomenon puts tremendous pressure on the global health care system. For instance, the health expenditure in the European Union is expected to rise by 350% by 2050 compared to an economic growth of only 180% in the same timeframe (Espinoza, 2011). The Directorate General for Economic and Financial Affairs reported that the provision of long-term care (LTC), in particular, will pose an increasing challenge to the sustainability of public finances in the European Union, due to an aging population (Lipszyc et al., 2012).

Evidently, many age-related diseases are fostered by a lack of physical, cognitive, and social activities. Increasing the level of activity has many benefits for older adults (Ehrari et al., 2020) and can improve their level of independence (McPhee et al., 2016). Specifically, numerous studies demonstrated that increasing the activity level can bring multiple benefits to older adults such as maintaining muscle strength (Garber et al., 2011), reducing falls (Sherrington et al., 2011), mitigating depression (Blumenthal et al., 1999), delaying cognitive decline (van Gelder et al., 2004), increasing independence, improving quality of life (Bize et al., 2007), and many more. Apparently, there are both an urgent need and substantial market potential to develop solutions to tackle these challenges.

[4] This chapter is partially based on the research article entitled "Developing a Smart Home Solution Based on Personalized Intelligent Interior Units to Promote Activity and Customized Healthcare for Aging Society" (Hu et al., 2020a) published in Journal of Population Ageing, Volume 13, Issue 2, and has been reproduced here with the permission of the publisher, see appendices. The authors retain the copyright of this publication according to the publisher (see Appendix IV: Letters/statements of reuse permission from publishers). Authors' contribution: R. Hu (correspondence, conceptualization, literature review, requirements engineering, design, modeling, visualization, writing-original draft preparation, writing-review and editing), T. Linner (requirements engineering, conceptualization), J. Trummer (co-design, visualization), J. Güttler (conceptualization, sensor development, programming), A. Kabouteh (sensor development, programming), K. Langosch (literature review), T. Bock (conceptualization, supervision).

[5] Archilochus (680 BC-645 BC): Ancient Greek poet.

Based on a brief overview of the state-of-the-art research, the objectives were stated, and the methodology used in this development was reported. In the following sections, this chapter presents an innovative smart home solution based on elderly-oriented smart furniture to encourage activity and customized healthcare in the context of aging society. Firstly, the methods used in the development are introduced. Furthermore, the results the development of the system as well as the concept for deployment are presented. In addition, a strategy for testing and exhibition of the system is reported.

3.1 Methods

One of the major goals of this research is to overcome key shortcomings of aforementioned smart environments by installing functionality into easily deployable and mass customizable furniture elements. These furniture elements can be prefabricated and preconfigured in workshops or factories and can be deployed easily in contrast to conventional smart home technology. It aims to generate a novel form of living support and activity promoting toolkit for older adults and eventually liberate family members or relatives (informal caregivers) from tedious and repetitive tasks involved in taking care of the elderly person. Through this step the informal caregivers can invest more time into the emotional support. During the development and implementation of these technologies, modularity will be one of the main considered aspects, in order to achieve easy integration to the environment and minimize modifications of the environment. Furthermore, the outcomes of this research will allow European industries, including small- and medium-sized enterprises, to capitalize on the European high-tech know-hows, making Europe a world leader in prevention technologies, services, and underlying ICT healthcare platforms, and meanwhile tackle the ultimate crisis of rising healthcare expenditures. The key methods of this research are presented as follows.

3.1.1 An interdisciplinary approach

Today, interdisciplinarity has become more and more crucial to the continuing advancement of science and technology. It is especially true for the development of gerontechnology systems. According to Bronswijk et al., gerontechnology is defined per se as “an interdisciplinary field that links existing and developing technologies to the aspirations and needs of aging and aged adults” (Bronswijk et al., 2009). Therefore, an interdisciplinary approach is necessary in the development of the REACH system. The project was led by a truly interdisciplinary consortium consisting of 17 partners from research universities and institutions, industry companies, and care facilities, covering various expertise and topics including but not limited to industrial design, architecture, mechatronics, computer and data science, medicine, nutrition, business strategy, finance, safety management, curation, and standardization. This approach can greatly benefit the execution of the project’s R&D and improve the acceptance of the developed products among older adults.

3.1.2 Touchpoints and Engine concept

In the project, an experimental, interdisciplinary sensing-monitoring-intervention system is developed that can be placed unobtrusively in various care settings and living environments of older citizens. The system aims to 1) use a variety of sensors to detect specific vital signs, behavioral patterns, and health status; 2) predict future health status, risks or events; and 3) anticipatorily provide a series of customized health products and services that support and promote physical activities. As a result, the Healthy Life Years (HLY) of older adults would increase, and their time spent in LTC facilities would be reduced (Bock, 2017).

Therefore, the research team developed the “Touchpoints and Engine” concept as a comprehensive solution of the system architecture for the research project. It further guides the detailed structural relation between the subsystems of the project. With the “Touchpoints and Engine” concept, the product-service-system architecture of REACH is divided into six manageable research and development clusters: four Touchpoint clusters (in other words, work groups each focusing on a specific topic within the project, including Touchpoint 1: Personal Mobility Device, Touchpoint 2: Active Environment, Touchpoint 3: Socializing & Nutritional Monitoring/Intervention, and Touchpoint 4: Gaming & Training System) that represent tangible connections between users (e.g., seniors, caregivers, physicians, etc.) and the REACH system; one “Engine” cluster, which is a cloud-based digital platform serving as the brain of the project; and one “Interface” cluster, which comprises a set of means that allow the Touchpoints and other products and services to interact with the Engine. Each cluster is associated with a dedicated and independent development team coming from the project consortium members (see Figure 3-1) (Linner et al., 2017). The work presented in this thesis is mainly related to Touchpoint 2 - Active Environment.

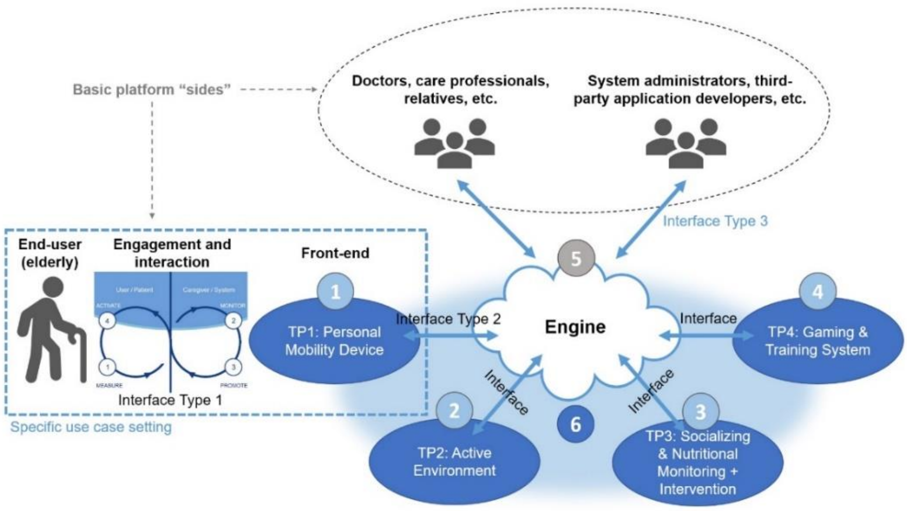


Figure 3-1: “Touchpoints and Engine” concept in REACH

3.1.3 Determining users’ requirements

In order to have a successful development process, it is important to conduct requirements analysis before the design process starts (Andersen et al., 2017). A description of the target user including the user environment and an analysis of the entities associated with the user were performed. Various methods were applied to describe and analyze these key components of the REACH system, including describing use cases, defining personas, creating experience maps, and analyzing stakeholders (Schäpers et al., 2017). Subsequently, the major hypotheses of four Touchpoints were concluded based on these analyses. For example, in Touchpoint 2, the hypothesis is formulated as follows: the REACH system based on smart furniture elements with sensing systems enables the patients to reduce the duration of their hospitalization, reduce decline after discharge, reduce risk of readmission, and be able to perform their ADLs with reduced support from professional caregivers.

Based on the result of the requirements engineering, the extracted raw requirements were further formalized and assigned to following specific requirements categories:

(1) Health Outcome Requirement (HOR)
(2) Transition Requirement (TR)
(3) Project Implementation Requirement (PIR)
(4) EU, Funding, and Call related Requirement (EFCR)
(5) Regulatory Requirement (RR)
(6) Business, Market and Innovation Management (BMIR)
(7) System Architecture Requirement (SAR)
(8) Stakeholder Requirements (SR)
(9) Non-Functional System Requirement (NFR)
(10) Functional System Requirement (FSR)
(11) Data Management and Ethic Requirements (DMER)
(12) Business, Market and Innovation Management (BMIR)

All outcomes of the conducted activities of requirements engineering (e.g., stakeholder analysis, co-creation workshop, analysis of best practice, business strategy, motivation analysis, data management, ethics study, intellectual property management, etc.) were systematically summarized, and the key points were extracted and translated into raw requirements.

The relevant requirements of Touchpoint 2 can be materialized by a series of Personalized Intelligent Interior Units (PI²Us). The PI²U is a special type of smart furniture that seamlessly integrates the required concepts and functionality into the different use case settings. This chapter focuses on a series of PI²Us developed by the project team in Touchpoint 2 (i.e., the "Active Environment" work group of the project). The relevant PI²Us include SilverArc, MiniArc, SilverBed, iStander, and ActivLife. The term "Silver" implies the color of older adults' hair. It is also in line with the booming silver economy.

This following tables outline the most important requirements relevant to the PI²Us (see Table 3-1, Table 3-2 and Table 3-3). An identification code (ID) was used to identify each requirement, allowing it to be tracked back to its origin in the requirements engineering report (Linner et al., 2017). The column "functions based on requirements" describes in detail which element of each the PI²U needs to meet the specific requirement. The developed requirements list can serve as a guideline for the further detailing of the smart furniture and can facilitate an efficient workflow in the development process.

Table 3-1: Requirements for MiniArc and SilverArc

ID	Formalized requirements	Functions based on requirements
HOR001	Touchpoint Active Environment shall detect early and prevent the decrease of (micro) mobility in a care environment.	Training, nutrition
HOR003	Touchpoint Socializing & Nutritional Monitoring + Intervention shall detect physical activity in relation to eating habit.	Projection screen, projector, Kinect, software
HOR008	Touchpoint Socializing & Nutritional Monitoring + Intervention shall give personal advice on food intake in combination with physical activity recommendation.	Projection screen, projector, software
TR004	Touchpoint Active Environments shall develop sensors as modular add-ons that are separable from the physical product.	Projection screen, projector, Kinect
SR075	Touchpoint Personal Mobility Device shall provide a screen and motion sensor to allow users to play games and follow mobility training instructions.	Projection screen, projector, Kinect
FSR031	Touchpoint Active Environment shall motivate patient to in and adhere to therapies/scheduled trainings/interventions.	Projection screen, projector, Kinect
FSR035	Touchpoint Active Environments shall use ambient sensors to detail overall vital signs.	Kinect
DMER102	Touchpoint Socializing & Nutritional Monitoring + Intervention shall develop a universal user interface/app that can be part of socializing and cooking environments or furniture or displayed on a smart phone or similar.	Projection screen, projector, Kinect
BMIR001	A modular conception shall ensure that potentially versions for home and long-term assistance/care can be generated.	MiniArc and SilverArc version (Modularity)
BMIR002	The Touchpoint shall provide value-based, personalized and preventive health care.	Training, software, MiniArc and SilverArc version (Modularity)
BMIR005	The Touchpoints shall serve as data gathering devices in use case adapted (and for the user personalized) form in the various use case settings.	MiniArc and SilverArc version (Modularity)

Table 3-2: Requirements for SilverBed

ID	Formalized requirements	Functions based on requirements
HOR001	Touchpoint Active Environment shall detect early and	Pressure mattress, thermal

	prevent the decrease of (micro) mobility in a care environment.	camera, verticalization function, tilting function
TR003	Touchpoint Active Environments shall use personal mobility device (TP1) and the Playware tiles based “gaming and training” system (TP4) later as additional interventions.	Docking function
TR004	Touchpoint Active Environments shall develop sensors as modular add-ons that are separable from the physical product.	Pressure mattress, thermal camera
FSR031	Touchpoint Active Environment shall motivate patient to in and adhere to therapies/scheduled trainings/interventions.	Easy transfer from SilverBed to iStander, docking function
FSR032	Touchpoint Active Environments shall increase the mobility of the patient through a combination and integration of “furniture” components to a seamless in-house “transfer and mobility chain”.	Docking function
FSR035	Touchpoint Active Environments shall use ambient sensors to detail overall vital signs.	Pressure mattress, thermal camera, heart monitoring
BMIR001	A modular conception shall ensure that potentially versions for home and long-term assistance/care can be generated.	Docking station, modular sensor-add-ons
BMIR002	The Touchpoint shall provide value-based, personalized and preventive health care.	Pressure mattress, thermal camera, heart monitoring, docking station
BMIR004	The business strategy shall ensure that each Touchpoint work as an independent product/innovation of a REACH industry partner as well as in the overall REACH system.	Docking station
BMIR005	The Touchpoints shall serve as data gathering devices in use case adapted (and for the user personalized) form in the various use case settings.	Pressure mattress, thermal camera, heart monitoring, docking station

Table 3-3: Requirements for iStander and ActivLife

ID	Formalized requirements	Functions based on requirements
HOR001	Touchpoint Active Environment shall detect early and prevent the decrease of (micro) mobility in a care environment.	Training, easy transfer from SilverBed to iStander, stand-up counter, activity monitoring
HOR002	Touchpoint Personal Mobility Device shall detect early the signs of frailty and the risk of falls.	Stand-up counter, activity monitoring
HOR007	Touchpoint Personal Mobility Device shall contain some basic physiological sensors that allow to monitor the training progress and outcomes.	Stand-up counter, activity monitoring
TR001	iStander shall make it possible to transfer the rehabilitation program to homes or care homes	Training, easy transfer

TR004	Touchpoint Active Environments shall develop sensors as modular add-ons that are separable from the physical product.	Stand-up counter, activity monitoring
TR005	Touchpoint Personal Mobility Device shall follow the person throughout the patient journey through different care stages.	Different variations of iStander (modularity)
TR006	Touchpoint Personal Mobility Device shall motivate elderly to train themselves safely, or in a community or together with care personnel in an institution to achieve a better level of mobility.	Different variations of iStander (modularity)
TR007	Touchpoint Personal Mobility Device shall be used as medical home or indoor fitness device.	Different variations of iStander (modularity)
TR008	Touchpoint Personal Mobility Device shall be mobile and compatible with existing furniture	Wheels, easy transfer
SR075	Touchpoint Personal Mobility Device shall provide a screen and motion sensor to allow users to play games and follow mobility training instructions.	ActivLife
FSR032	Touchpoint Active Environments shall increase the mobility of the patient through a combination and integration of “furniture” components to a seamless in-house “transfer and mobility chain”.	Wheels, easy transfer
FSR035	Touchpoint Active Environments shall use ambient sensors to detail overall vital signs.	Stand-up counter, activity monitoring
BMIR002	The Touchpoint shall provide value-based, personalized and preventive health care.	Docking function, Training, Stand-up counter, Activity Monitoring, Different variations of iStander (modularity)
BMIR004	The business strategy shall ensure that each Touchpoint work as an independent product/innovation of a REACH industry partner as well as in the overall REACH system.	Docking function
BMIR005	The Touchpoints shall serve as data gathering devices in use case adapted (and for the user personalized) form in the various use case settings.	Docking function, training, stand-up counter, activity monitoring, different variations of iStander (modularity)

3.1.4 Development principles

The design of system follows the principles of modularity, “good sensing”, and iterative development. The implementation of these principles in developing the Ambient Rehabilitation Kit is described as follows.

3.1.4.1 Modularity and platform strategy

Usually, there are six common types of modularity (see Figure 3-2) in present modular products, including slot modularity, bus modularity, sectional modularity, component-sharing modularity, component-swapping modularity, and cut-to-fit modularity (Mascitelli, 2004). The type of modularity applied to the PI^2Us mainly is bus modularity. It refers to when several different components can be attached to a standard structure. The type, number, and location of modules that can plug into the “bus” (i.e., platform) can substantially vary.

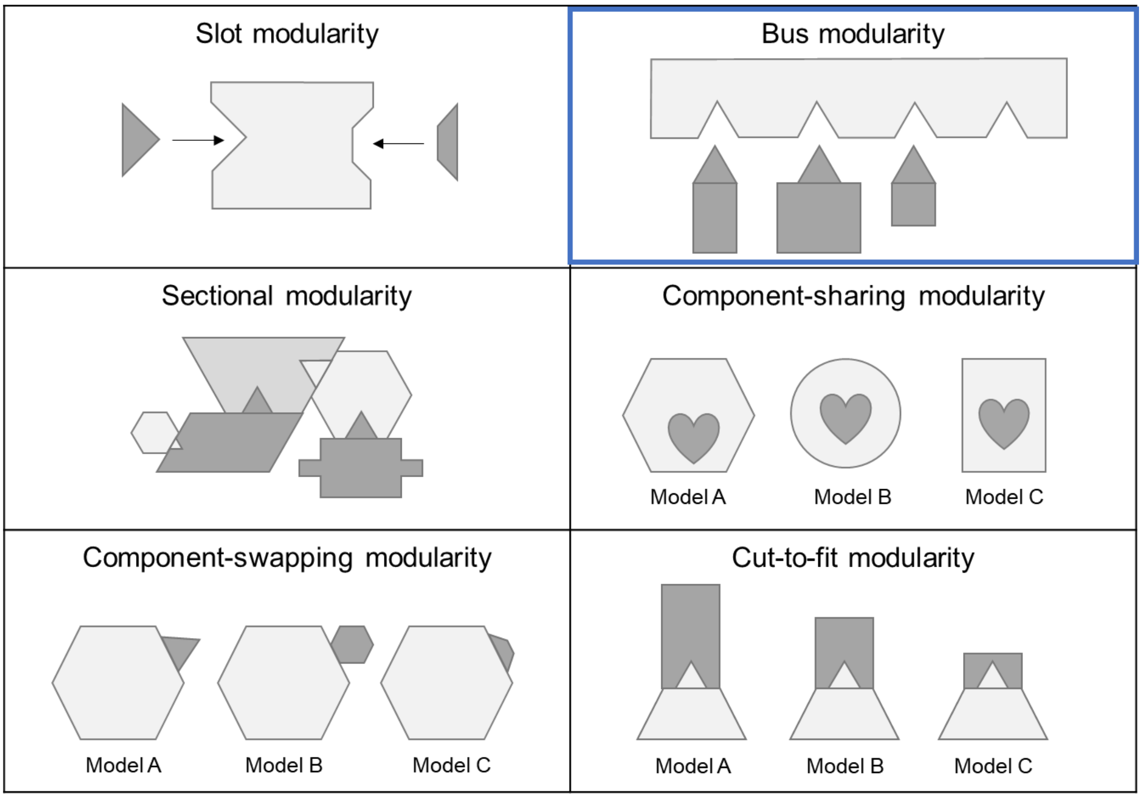


Figure 3-2: Types of modularity (adopted and redrawn from Mascitelli, 2004)

Platform has various definitions. According to Muffato and Roveda (2002), a platform is “a set of subsystems and interfaces intentionally planned and developed to form a common structure from which a stream of derivative products can be efficiently developed and produced” (Muffatto and Roveda, 2002). This definition emphasized the importance of the interface in a platform, which is often overlooked, although it influences the success of a product in the long term. The platform strategy is useful for mass production and especially mass customization. Its advantages includes reduced development time, decreased system complexity, reduced development and production costs, and enhanced ability to upgrade products (Simpson et al., 2006). It provides a structured modularity in more levels and a high degree of standardization (Jose and Tollenaere, 2005). In the case of PI^2Us, the lower-end product platforms (e.g., SilverArc, MiniArc, SilverBed, and iStander) can be scaled upwards into higher price-performance tiers through the addition of sensors, modules, and technologies. A platform can purposely be planned to be more or less modular. If a platform is highly modular in its design, the modules produced for the platform have the potential to be modular as well. Levels of modularity can differ between the different modules of the same platform (Tiwana, 2014).

3.1.4.2 "Good sensing" versus "bad sensing"

Today, sensors are widely used in almost all fields in society, including the healthcare industry. Health monitoring and assistance sensors can be categorized sensors into six aspects, namely ambient, digital traces, environment, high-dimensional, physiological, and wearable, see Table 3-4 (Cook, 2020).

Table 3-4: Health monitoring and assistance sensors by categories (adapted from Cook, 2020)

Category	Sensors
Ambient	Infrared, laser, magnet/contact switch, light, temperature, humidity, vibration, pressure, power usage, water usage, radio-frequency identification
Digital traces	Web browser cookie, social media record, purchase history
Environment	Location, outdoor walkability score, indoor/outdoor air quality, light levels, noise levels, light detection and ranging
High-dimensional	Camera, depth sensor, thermal sensor, radar, microphone array
Physiological	Respiration, pulse, galvanic skin response, body temperature, cortisol level, blood pressure, blood oxygen saturation, electrocardiogram, electroencephalography, electromyography, electrooculography
Wearable	Accelerometer, magnetometer, gyroscope, compass, location

Technically speaking, there are no "good sensors" or "bad sensors" per se. However, choosing the appropriate sensors in older adults' living environment requires extra caution. Pol et al. reported that using sensors to monitor older adults in their living environment is appropriate because the sense of safety is more critical than privacy, as long as those sensors do not take photos/videos or record sounds (Pol et al., 2016). Moreover, Ehrari et al. reported that in an interview about older adults' attitude on health monitoring, 81% (17 out of 21) interviewees accepted the idea of sensor-based monitoring, but all of them rejected the idea of camera-based monitoring, indicating that the type of sensor highly matters (Ehrari et al., 2018). Valk et al. noted that many older adults experience barriers to the adoption of wearable technology, although it can provide helpful feedback regarding their health status (Valk et al., 2018). Furthermore, another study suggested that although wearables do not invade privacy, they have many drawbacks that prevent them from being worn constantly, such as short battery life, causing discomfort, and leading to skin allergy and rash (Gochoo et al., 2021).

Therefore, in order to increase older adults as well as their caregivers' acceptance of gerontechnology, this research chose privacy-preserved sensors (i.e., excluding intrusive sensors such as video camera, voice recorder, fingerprint scanner, iris scanner, etc.) that can be embedded seamlessly into older adults' living environment as data collection tools. Figure 3-3 shows the criteria of sensor selection in this research.

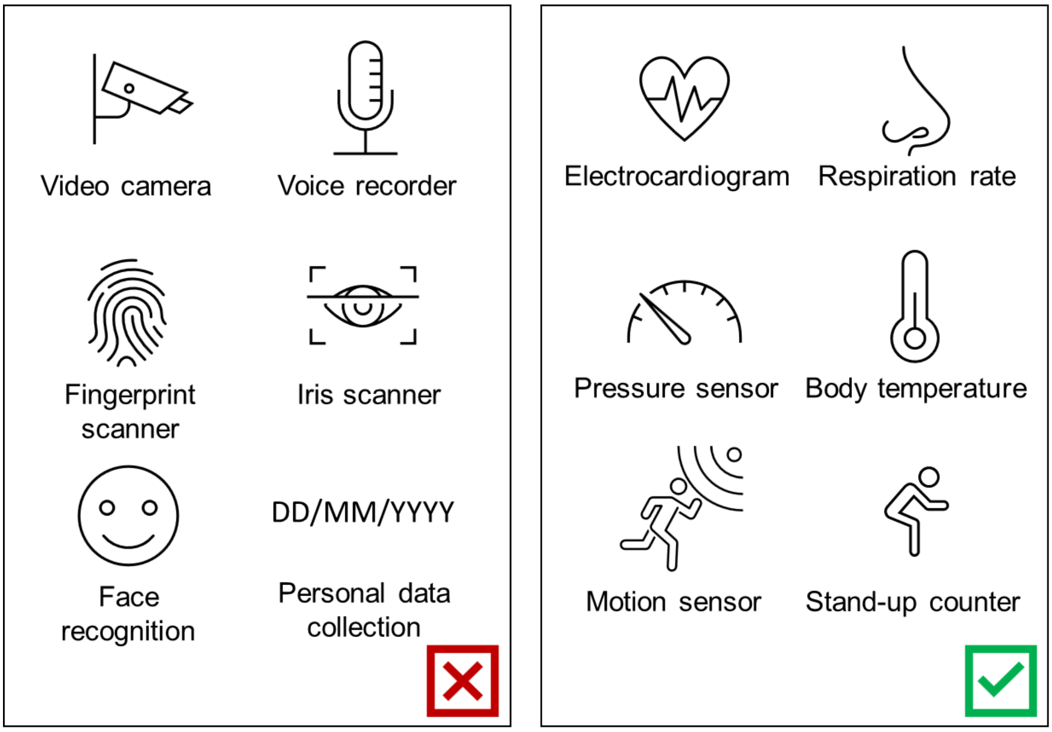


Figure 3-3: "Good sensing" vs. "bad sensing" - criteria of sensor selection in this research

3.1.4.3 Iterative development

Design iteration is a common practice in product design and is proved to be efficient and suitable for developing prototypes according previous research (Ren et al., 2016). Therefore, the development process of the PI²Us follows iterative design principles on both hardware and software levels, which allows the project team to optimize the products through prototyping, testing, analyzing, and refining (Cockburn, 2008). As illustrated in Figure 3-4, the project team completed the development and functionality testing of first or second prototypes of relevant PI²Us. Future versions of the PI²Us are currently being developed and will be tested with elderly users regarding usability and performance.

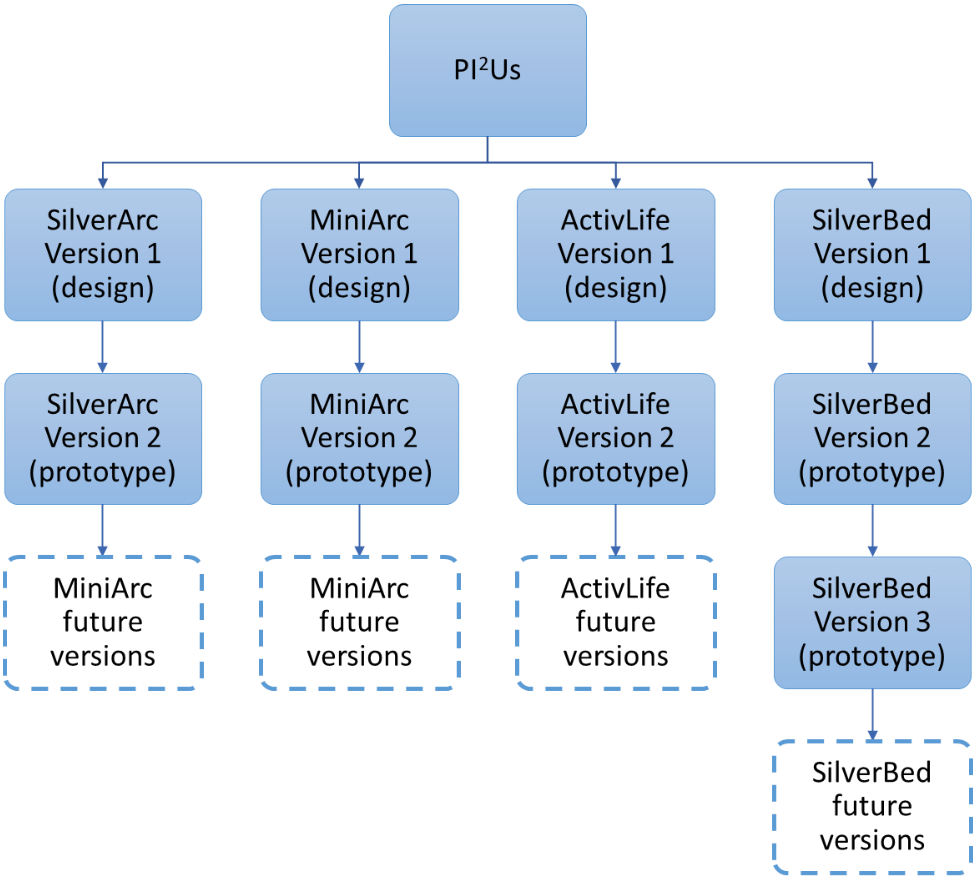


Figure 3-4: Iterative design process of the PI²Us

3.2 Development of the PI²Us

In the following sections, the designs and prototype iterations of PI²Us in Touchpoint 2 are reported and the results of the functionality testing activities based on the PI²Us are presented in detail, including SilverArc, MiniArc, SilverBed, iStander, and ActivLife.

3.2.1 SilverArc

The SilverArc was developed for the use in a large kitchen or dining space (e.g., a community kitchen). It offers an interactive projection area in the kitchen, where recipes and games can be displayed. It also has a foldaway projection area where a training program can be displayed (see Figure 3-5). The round shapes, wood material, and bright colors give the SilverArc a warm and inviting presence.

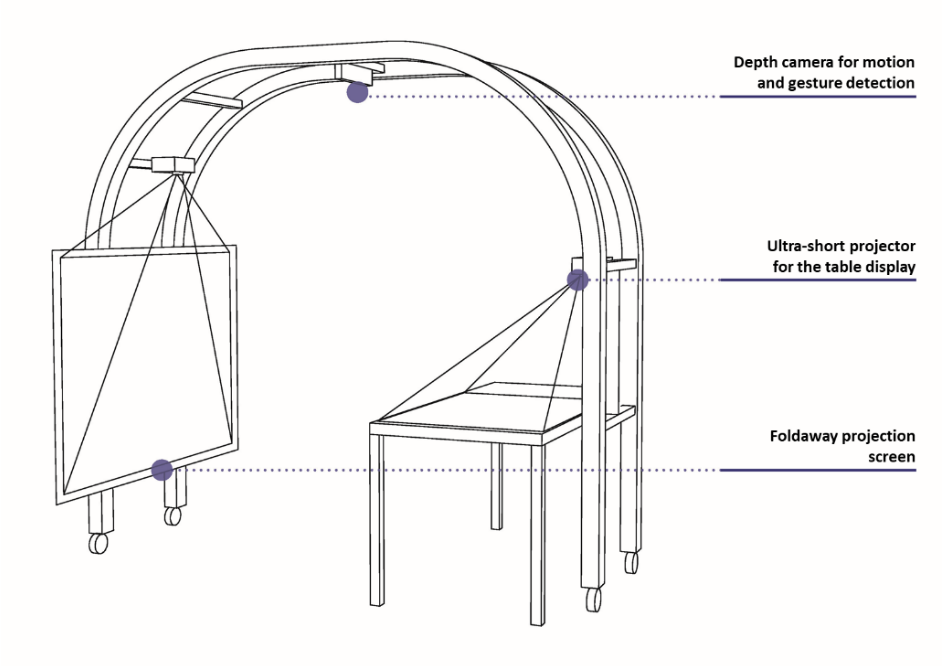


Figure 3-5: Preliminary design of the SilverArc

The preliminary design of the SilverArc was not suitable to be converted directly into a prototype. For example, the material of the prototype and the final product differ substantially. After evaluation, it was decided that MayTec's modular aluminum profile system is suitable for building the prototypes. MayTec GmbH offers a wide range of modular profiles, accessories, and different connection possibilities (http://www.maytec.com.de/). Using the aluminum profile scheme, simple modifications can be created after the first test. In conjunction, in order to reduce costs, the curves in the prototypes were omitted because they mainly serve an aesthetic function and are not necessary for the functionality testing. However, it is important to manufacture future iterations of the prototypes using the shape and material proposed in the preliminary design, and test them with the older adults regarding the usability and performance of the PI^{2}Us.

Figure 3-6 shows in detail how the technical equipment is integrated into the prototype. An ultra-short projector is fixed above the projection screen. It was deliberately decided against a mounting under the projection area, since the dust load for the projection lens would increase. Depth cameras are attached to a sliding system for easy positioning adjustment. The whole device is powered by a mini-computer (i.e., Intel NUC X86 Mini PC).

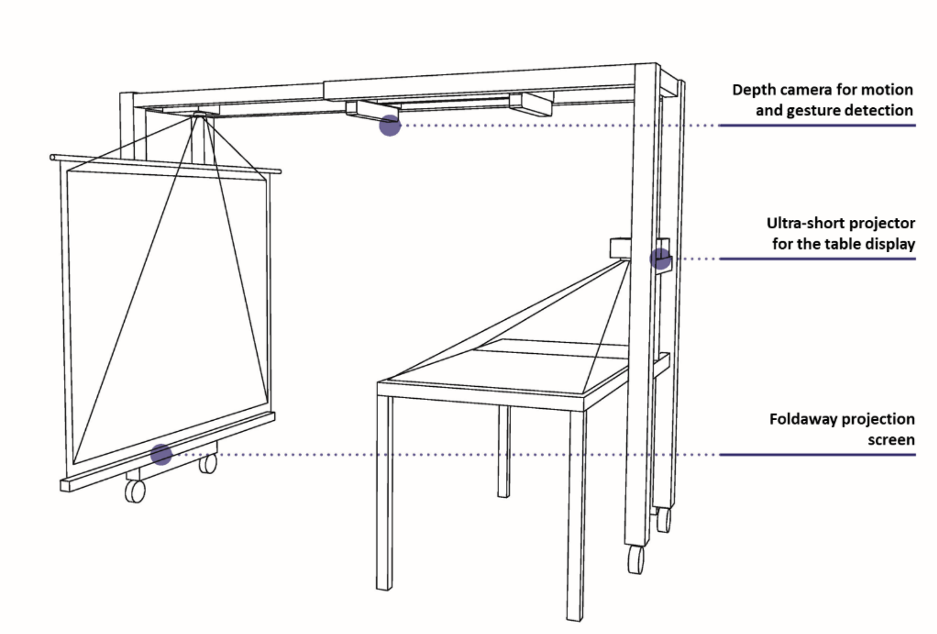


Figure 3-6: Prototypical version of the SilverArc

In order to make the system easier for older adults to use, the project team developed an intuitive and user-friendly graphical user interface (GUI) that can be applied to both SilverArc and MiniArc. The major functions of the GUI include, but are not limited to time, calendar, weather, appointment reminder, email, game center, and photo gallery (see Figure 3-7). The size of the GUI can be adjusted according to various use case scenarios, including tables, projection screens and walls. The users can easily use their fingertips as the mouse to operate the program.

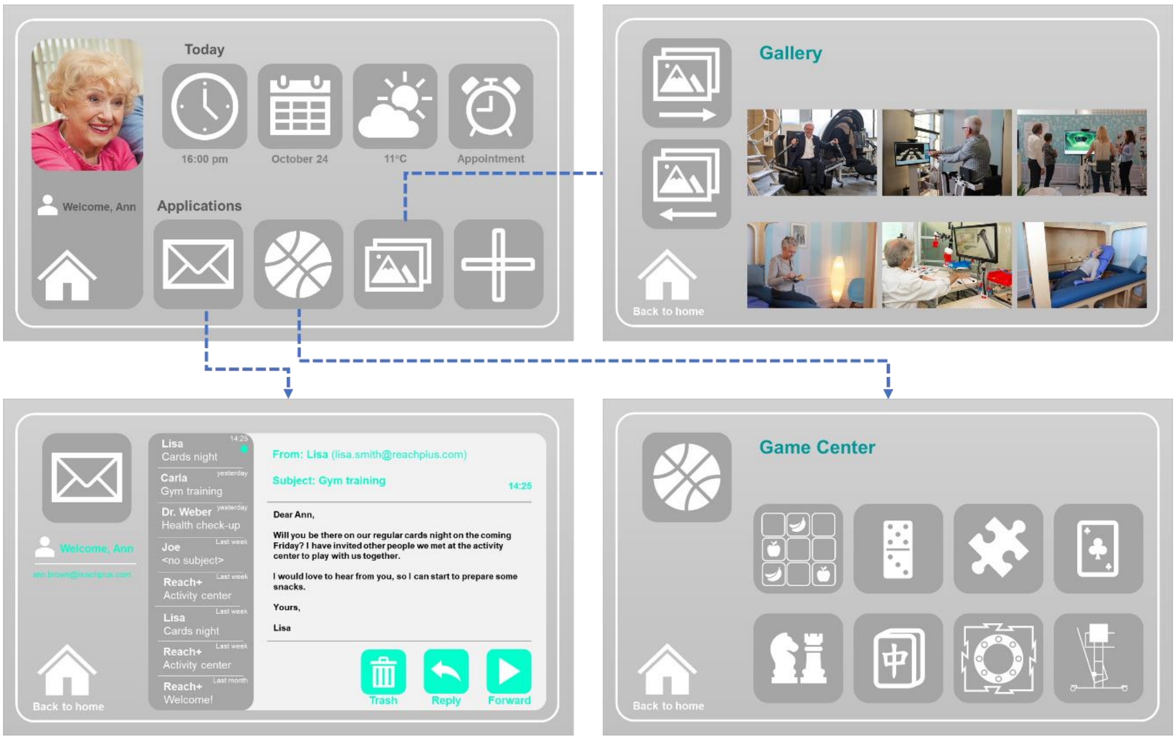


Figure 3-7: Design of the GUI's home screen and second screens

In particular, a security code was embedded into the GUI program to prevent user's slow motion to trigger the same button several times at once, which would lead to a call of the same layer multiple times that would consequently crash either the RAM or CPU of the mini-computer. On the gesture recognition input (see Figure 3-8), a direction validation was added, which enabled the interactive table to be used from all sides.

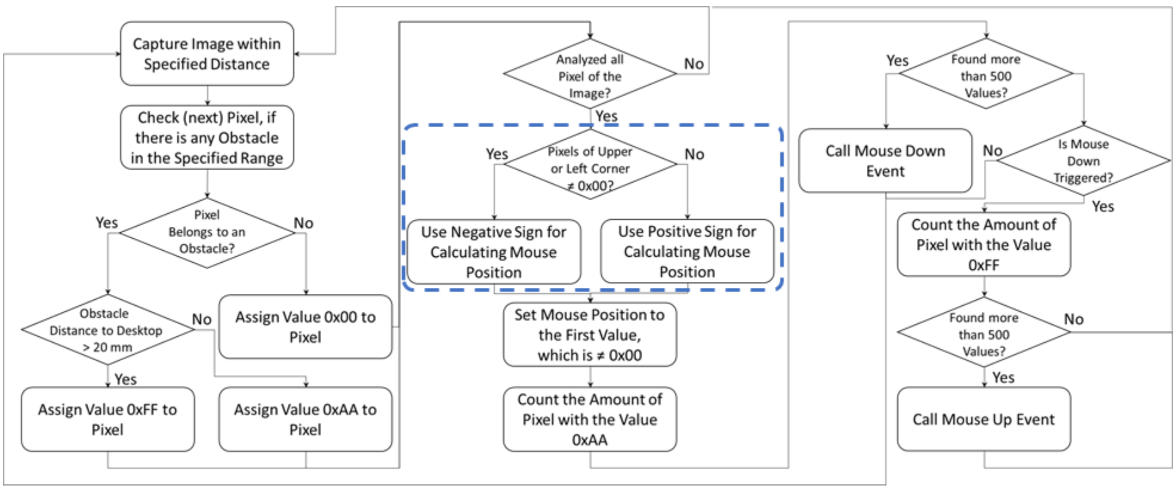


Figure 3-8: Gesture recognition algorithm flowchart of the SilverArc and MiniArc via the Kinect, including the newly added security algorithm marked in blue

3.2.2 MiniArc

The MiniArc can be considered as a flexible and smaller variant of the SilverArc, which is designed to assist in the training and moving of older adults who are hospitalized or live in smaller apartments. An ultrashort projector can project the user interface on its foldaway table or on a separate table as needed. In addition, a motion-sensing camera (Microsoft Kinect) is integrated to detect the user's gestures, enabling the interactive gaming function. There is another projector on top of the device that can project supplementary information onto a wall. This prototype was fitted with wheels and is thus mobile. The philosophy of inclusive design was also considered so that a user in wheelchair can easily push the wheelchair in between the wheels (i.e., 895mm). Figure 3-9 and Figure 3-10 respectively demonstrate the preliminary design and the final prototypical version of the MiniArc.

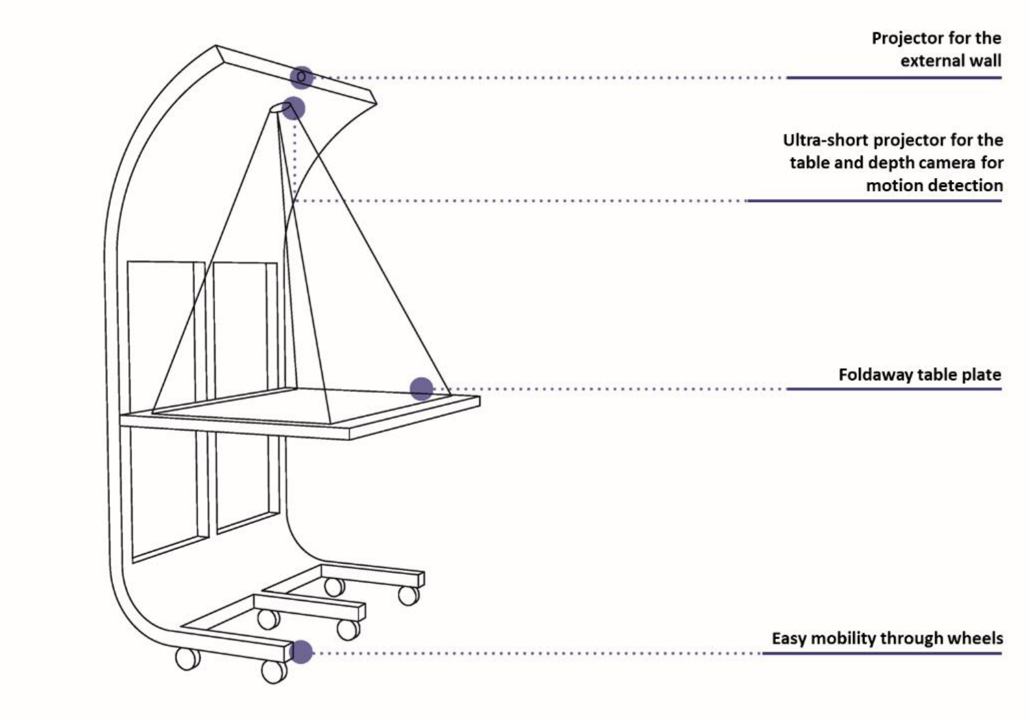


Figure 3-9: Preliminary design of the MiniArc

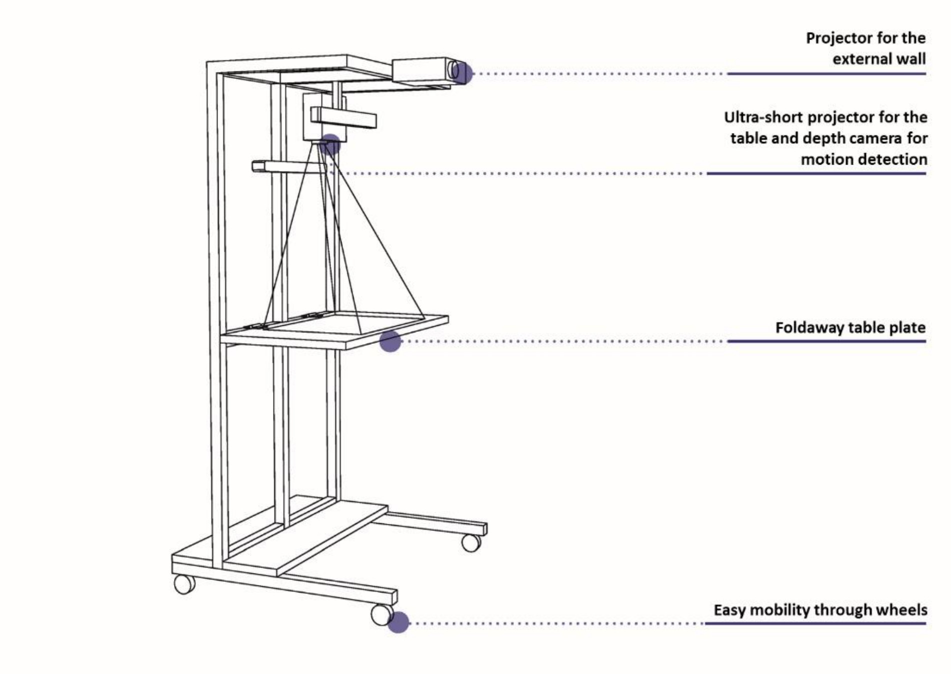


Figure 3-10: Prototypical version of the MiniArc

3.2.3 SilverBed

As shown in Figure 3-11, the first design of the SilverBed resembles a normal bed for private use. As a special feature, an arc-shaped frame covers the entire length of the bed, which allows for an easy integration of sensors and technologies such as a thermal camera for breath detection and a projector for the bed. The height of the bed can be adjusted. On the one hand, this feature makes it possible for the caregivers to work at a height that is comfortable for their stature. On the other hand, the lowest height of the bed facilitates the transfer of the patient from the bed to other functional units such as a wheelchair. The bed can be set to both a sitting and a vertical position. The sitting position allows the bed to support the patient and the nurse in many tasks such as eating, while the vertical position is especially apt for patients in an intensive care unit (ICU), who must perform the transfer from lying to vertical position. The passive standing that is enabled by a standing frame aims to improve respiratory function and cardiovascular fitness, increase the levels of consciousness, functional independence, and psychological well-being, and reduce the risk for delirium and the adverse effects of immobility (Stiller and Phillips, 2003).

In order to adapt the bed system to each patient's needs, a modular docking system was integrated into the design. Modules providing additional functions such as a toilet, physical training, transfer, and mobility can dock at different positions in the frame of the bed and are symmetric and self-guided. For example, with the leg-curl training module (see Figure 3-11), the patient can rest on their abdomen and use their legs to move the weight up and down. Training muscles is imperative to the performance of daily tasks.

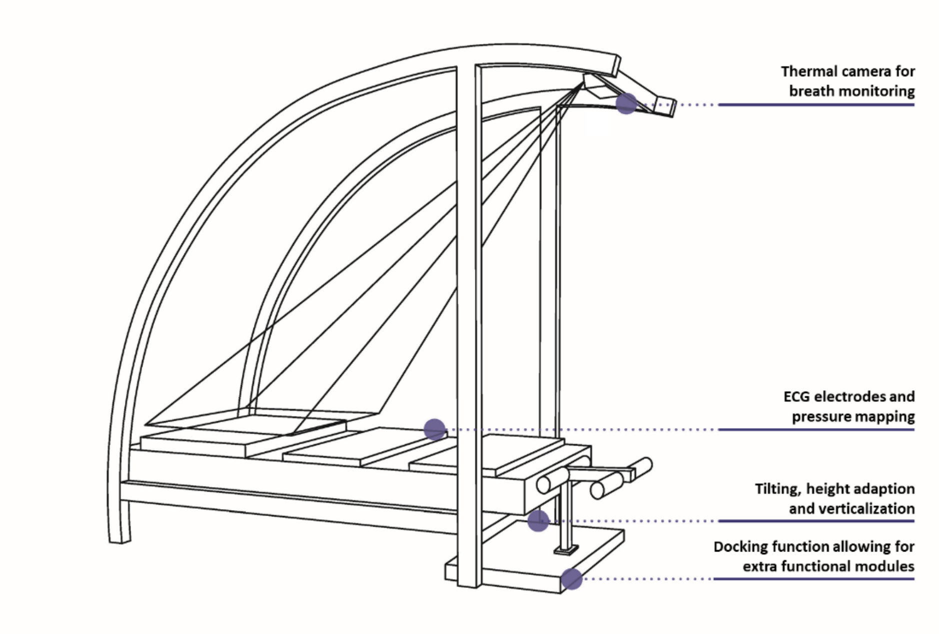


Figure 3-11: Preliminary design of the SilverBed

To validate the concept of the SilverBed, a prototype was planned and built using the aforementioned aluminum profile system. Figure 3-12 shows the final design of the SilverBed prototype that was manufactured. After testing the first prototype, the project team discovered several drawbacks in this version despite fulfilling the majority of assumptions concerning functionality during the laboratory testing. For example, the load capacity of the position changing mechanism is not satisfactory compared to a professional hospital bed. Furthermore, the heavy usage of aluminum material makes it difficult to appeal to seniors especially when it is used in resting space.

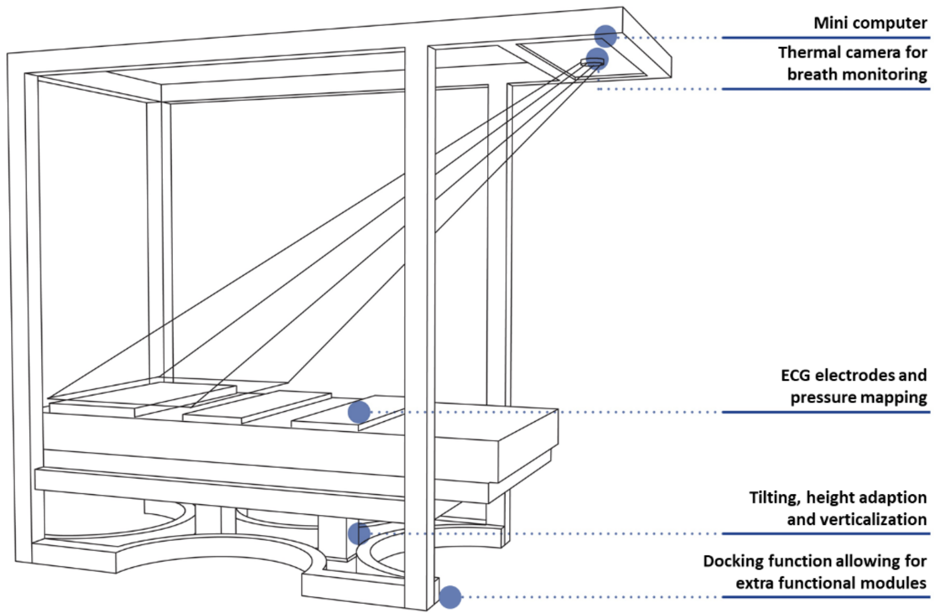


Figure 3-12: First prototypical version of the SilverBed

Therefore, the project team revised the design with a different approach: to incorporate a Sara Combilizer with a carpentry-based Activation Cockpit around it. The Sara Combilizer is a combination of a chair and a tilt table developed by REACH partner Arjo, which can allow even immobile patients to be moved to a sitting, standing, or supine position in a comfortable and safe manner (McWilliams et al., 2017). The activation cockpit is another key element of this version of the SilverBed. It expands the functionality of Sara Combilizer and provides a surrounding where older adults with reduced mobility can not only sleep in, but also spend their day in an active way. With this new version of SilverBed, physical exercise is offered in combination with entertainment, motivating its users to become more active. More importantly, health functions can be also integrated such as vital signs monitoring (will be described in detail later) and direct access to drinking water. Meanwhile, the ambient lighting function based on light-emitting diode (LED) is also integrated in the SilverBed, providing soft lighting with various hues (i.e., 16+ million colors) which can improve the user's mood and emotion (Valdez and Mehrabian, 1994). Additionally, docking function to other rehabilitation devices can be included as well, allowing users to transfer safely between the Sara Combilizer and iStander. The system is highly modularized so that specific add-ons and plug-ins can be tailored for each individual and included in the Activation Cockpit in endless possible combinations. Being highly adaptable, the Activation Cockpit is suitable for both home and hospital use (see Figure 3-13).

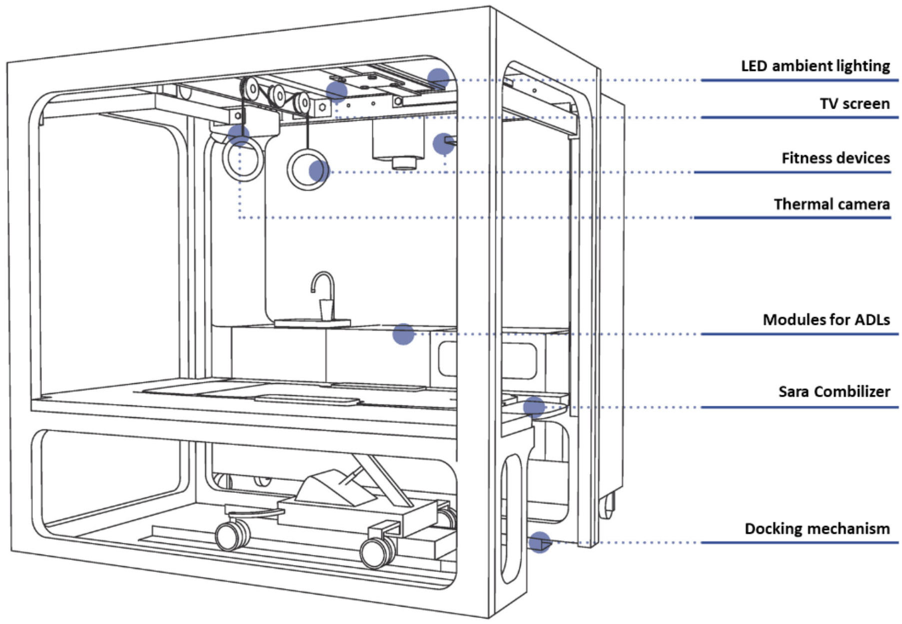


Figure 3-13: Second prototypical version of the SilverBed comprising the Activation Cockpit and Sara Combilizer

Figure 3-14 shows the second prototype of the SilverBed made of wood deployed in TUM's testing apartment. Figure 3-15 demonstrates an older adult using the SilverBed and adjusting his body autonomously into three positions (e.g., lying, sitting, and standing) in order to perform ADLs with the help of the SilverBed.

Figure 3-14: Second prototype of the SilverBed

Figure 3-15: An older adult autonomously testing the SilverBed in three positions: lying, sitting, and standing

Furthermore, a hospital variant of SilverBed using different material, abiding stricter hygiene standards, and providing undisturbed access was proposed. As care routines require especially the hospital variant to provide access from all four sides, a generous amount of space was left at the head side and both left- and right-hand sides. Together with the possibility of installing curtains at all four sides, it can give patients an increased feeling of comfort and privacy, which is important in the hospital environment. A large array of functions can be integrated in a modular manner to the main frame that is hung from the ceiling (see Figure 3-16).

Figure 3-16: Design of the hospital variant of SilverBed

3.2.4 iStander and ActivLife Training/Gaming Platform

The iStander was co-developed with the REACH project partner Alreh Medical to activate the physical and mental activity of people of old age whose daily activity level has decreased. It is used to prevent older adults from falling and provides effective support for cognitive processes through the combination of physical and cognitive exercises (Kozak et al., 2017). It can further facilitate the mobility and transferability of older adults within their living environment. Due to its flexibility and comparable size to a small treadmill, the system can be easily deployed in spaces such as living rooms and bedrooms (see Figure 3-17). The device is equipped with a mechanism to assist the user to stand up and to perform motor exercises of the ankles, knees, and hip joints. A special corset and a seat ensure safety during the exercises that strengthen the back and abdominal muscles by lifting the legs. It also allows the user to maintain a safe, upright standing position and perform balance exercises as well as exercises where the upper body parts are activated using the ActivLife Training/Gaming Platform (see Figure 3-18).

Figure 3-17: First version of iStander and ActivLife Gaming Platform (Image: Alreh Medical)

Figure 3-18: Customized prototypes of iStander and ActivLife Gaming Platform deployed in TUM's laboratory

The ActivLife Gaming Platform employs the VAST.Rehab software as its gaming interface for rehabilitation. VAST.Rehab is easy to learn and use, and also has a variety of exercises that can be customized for each older adult separately (see Figure 3-19). Research showed that gamification of physical activities can change the way older adults feel about their daily exercises and motivate them to get actively involved in the rehabilitation process (Brox et al., 2011). Each game can be controlled by different types of movement. The goal-setting approach unobtrusively pushes older adults to exercise more by rewarding them with higher scores and levels in the games (see Figure 3-20).

Figure 3-19: Screenshot of the fun and elderly-friendly gaming interface of VAST.Rehab

Figure 3-20: Older adult enjoying ActivLife's games with gestures at TUM's laboratory

3.2.5 Engine service

The REACH Engine consists of several subcomponents or clusters including a digital toolkit (analytics and Machine Learning elements, secure data communication, data transformation and platform solutions, privacy and security tools, software applications, etc.). One “Interface” cluster is composed of a set of elements that allow different touchpoints to connect and communicate with the REACH Engine elements and with other stakeholders (older adults, doctors, etc.). The Engine has three main clusters: CARP platform from Technical University of Denmark (DTU), HSDP Platform from Philips, and Engine Platform from SmartCardia.

A major component of the Engine (Data Management Toolkit) is the CARP platform developed by DTU. In order to implement and showcase this aspect of the REACH project, it was planned to interface the CARP platform with two touchpoints in REACH (i.e., Touchpoint 2 and Touchpoint 4). The system architecture and detailed overview of this integration is presented in Figure 3-21.

In this section, development steps taken for integration and interfacing the touchpoint 2 with the CARP platform are presented. In order to integrate the touchpoint 2 with the CARP platform, a two-cycle iterative development plan was considered. Since both servers use the Secure Shell (SSH) protocol/program for transferring data, the general concept of modular scripts for data transmission is the same for both platform clusters (i.e., CARP and HSDP); only the syntax in the scripts is different, depending on the target cluster. Therefore, the exemplary server interface for the REACH Engine for Touchpoint 2 was demonstrated on the CARP cluster.

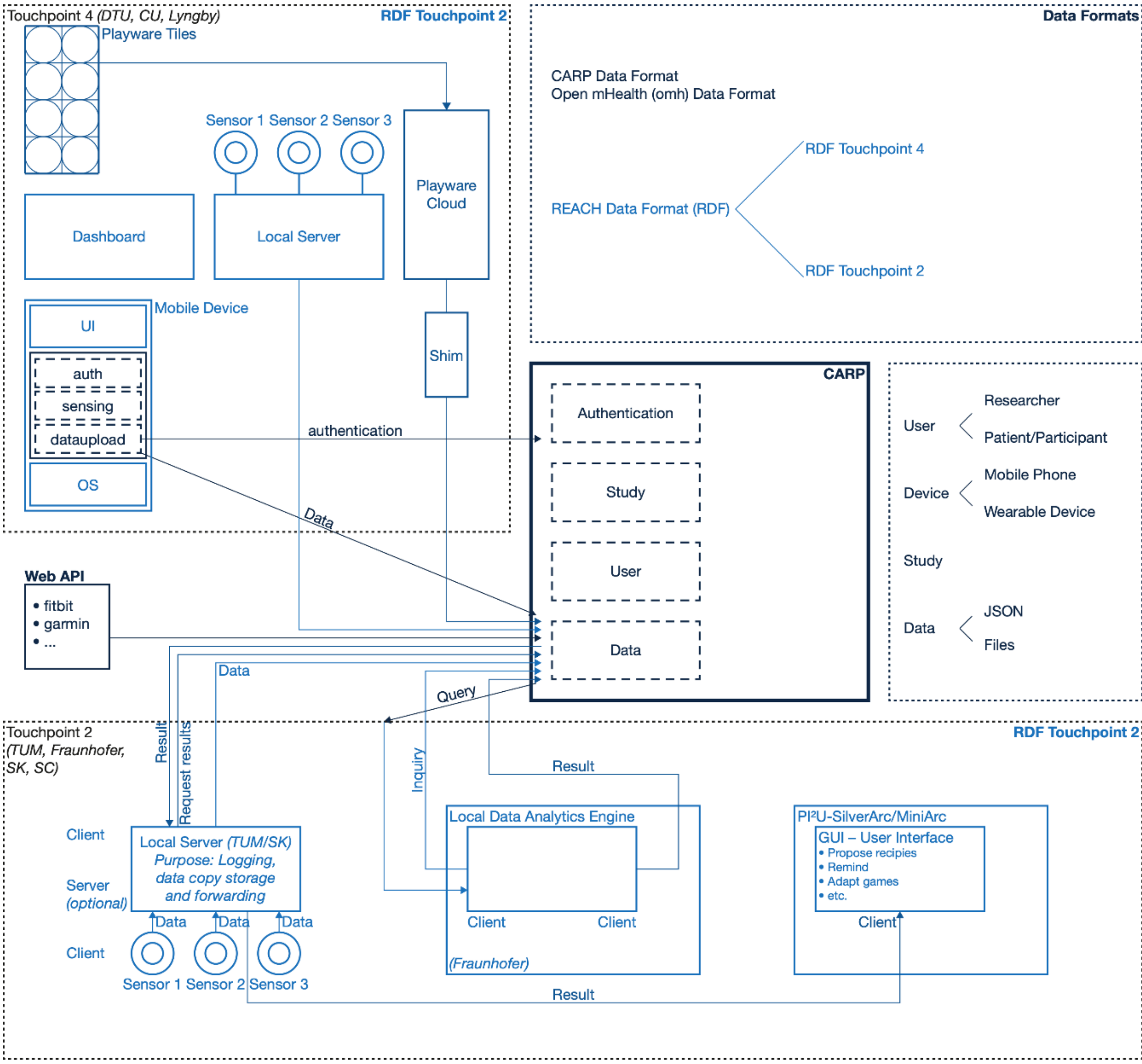


Figure 3-21: System architecture of data communication activities in the CARP platform

3.3 Solution for rapid implementation

As mentioned in the previous section, PI²Us developed in Touchpoint 2 materialize the project concepts and functionality seamlessly into the different use case settings. Based on the current outcomes from Touchpoint 2 as well as all other Touchpoints, the project team proposed a modularized smart home solution, namely the Ambient Rehabilitation Kit concept, which integrates all PI²Us and key technologies in REACH to create a complete interior living and care environment for older adults. Due to its modularity, selected parts of the Ambient Rehabilitation Kit can be easily adapted and rapidly deployed in different use case settings in Europe and beyond, which will then help the project to execute a series of testing activities. The proposal of this concept and its exemplary deployment in one use case setting of the REACH project are reported as follows.

3.3.1 The application of the Ambient Rehabilitation Kit concept

By implementing barrier-free design principles, the Ambient Rehabilitation Kit concept can be easily adapted and deployed in various living spaces such as community kitchen, activity room, and patient room, covering most life scenes of older adults. In these living spaces, rehabilitation devices in Touchpoint 1, smart furniture in Touchpoint 2, socialized nutrition solutions in Touchpoint 3, and gaming/training devices in Touchpoint 4 are seamlessly integrated to create a comprehensive experience of the REACH platform for the users (see Figure 3-22).

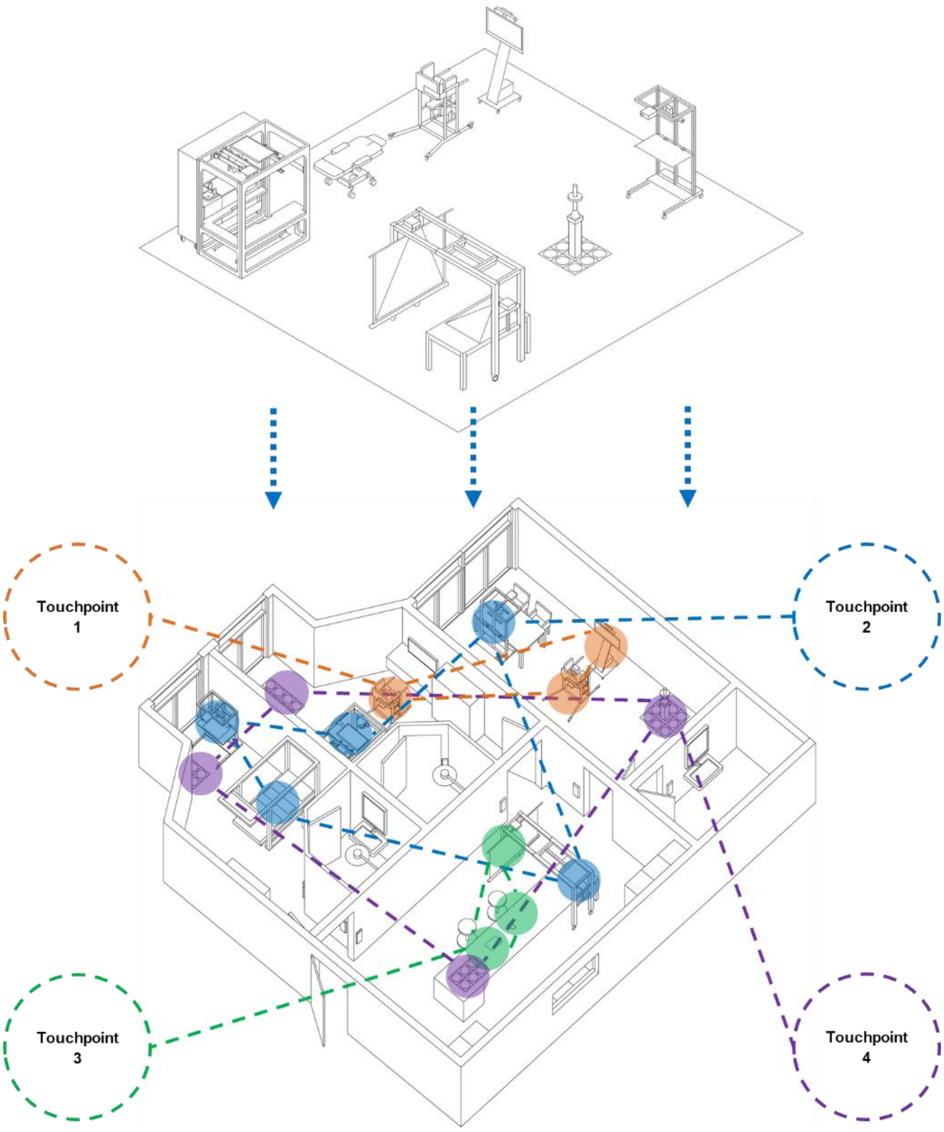


Figure 3-22: The Total Room Assistive Care Kit integrated in an exemplary care home

3.3.1.1 The community kitchen

The community kitchen serves as a key space for one of the most important daily activities – cooking and eating. It provides an ideal application space for technologies, particularly from Touchpoint 3 (i.e., the "Socializing & Nutritional Monitoring/Intervention" working cluster of the project). The older users of the community kitchen can cook and eat together with the help of state-of-the-art technologies. As shown in Figure 3-23, the SilverArc (or alternatively MiniArc) will project an interactive cooking table allowing older adults to cook in a smart and interactive way. Furthermore, older adults in the kitchen are encouraged to use a series of smartphone apps. In addition, healthy and customized food developed by Biozoon (Michail, 2016) can be provided to the older adults who use the kitchen. As a result, the seniors are expected to become more socially active and nutritionally healthy due to the usage of the community kitchen.

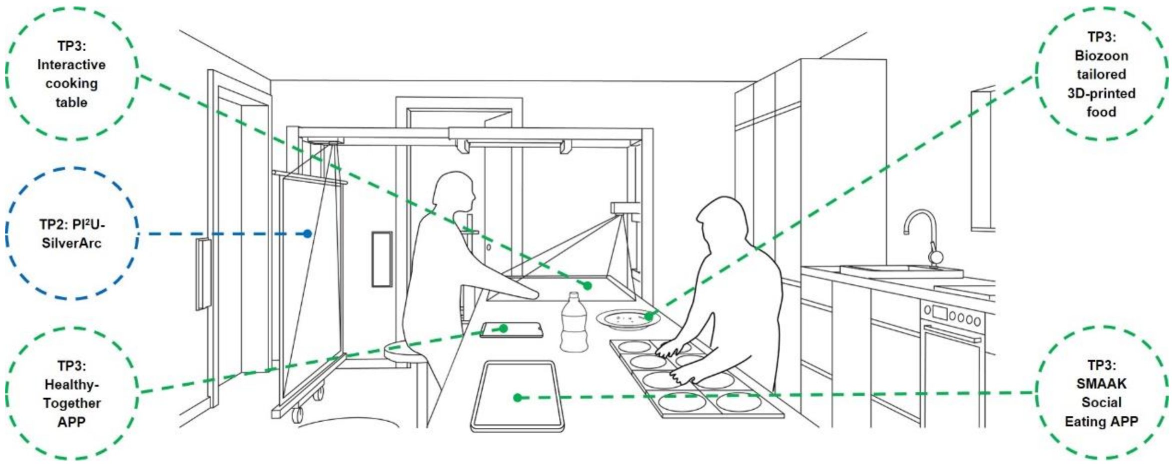


Figure 3-23: Simulation of the community kitchen

3.3.1.2 The activity room

One of the research's main objectives is to encourage the level of exercise of older adults. Therefore, the activity room provides a flexible space for older adults to become more physically and mentally active. In this room, the ActivLife gaming platform and the iStander training device (developed by Alreh Medical), the MiniArc in both table mode and mobile mode, and the Playware Moto Tiles (Liu et al., 2019) will be implemented to provide older adults with an active environment to improve their physical and mental health (see Figure 3-24).

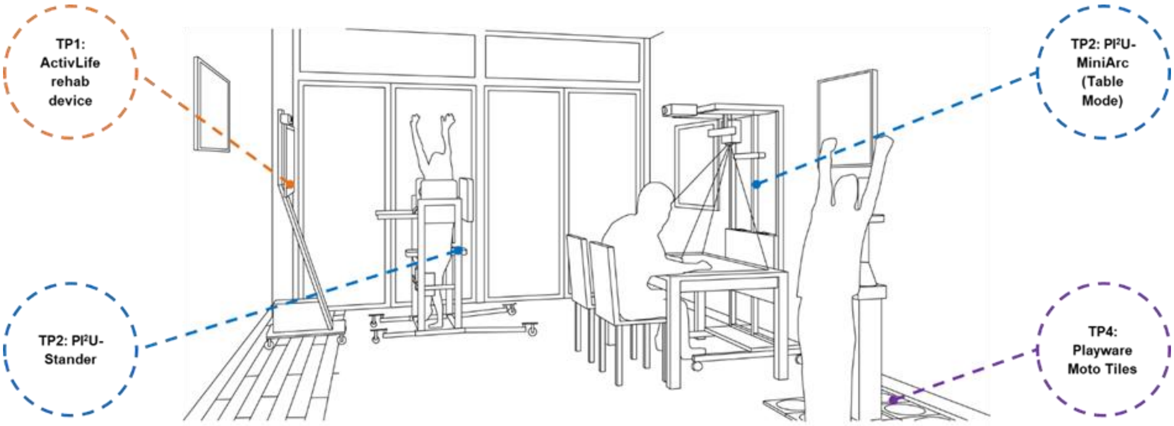


Figure 3-24: Simulation of the activity room

3.3.1.3 The patient rooms

In the patient rooms, older adults can live, exercise, and play cognitive games independently using the MiniArc. Meanwhile, when the patient is resting on the SilverBed, the bed can monitor the user's body temperature and respiration rate by using a thermal camera, the body pressure can be measured using the Pressure Mattress, and ECG data can be monitored by using ECG sensors on the bed (see Figure 3-25).

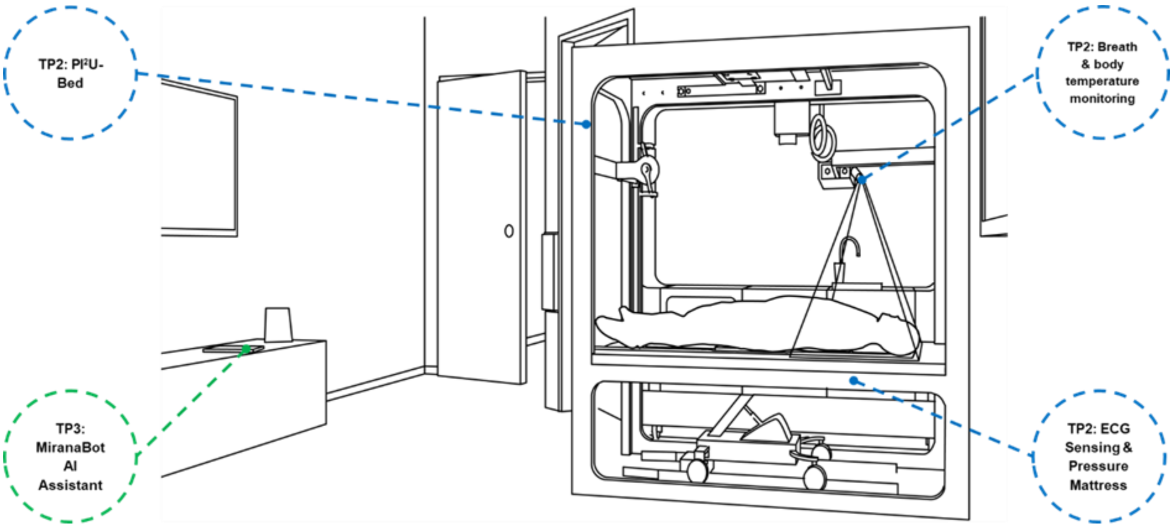


Figure 3-25: Simulation of the patient room type A

Figure 3-26 shows a variant of the patient room, in which the SilverBed raises to a vertical position, helping the user to stand up easily and transfer into an iStander with or without the help of a caregiver. The iStander serves as a training device for standing up as well as a mobility device to help the user to move to other areas easily (e.g., bathroom, kitchen, activity room, etc.).

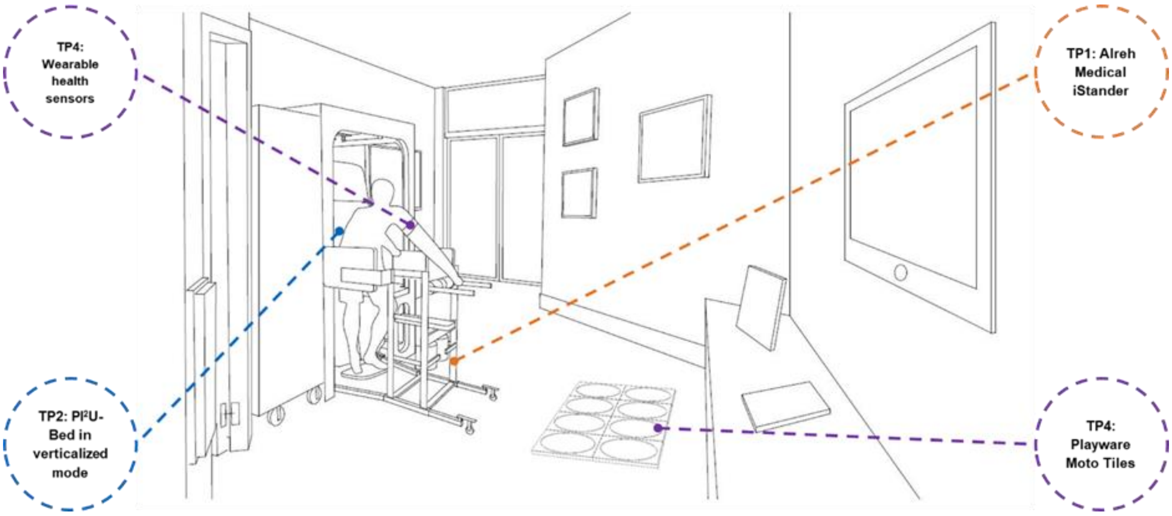


Figure 3-26: Simulation of the patient room type B

3.4 Strategy for testing and exhibition ("lab-field-showroom" approach)

After the manufacturing of the various PI²U prototypes, a series of testing and exhibition activities were carried out to verify the functionality, operability, and usability of the PI²Us. These activities followed a "lab-field-showroom" approach that is also an important component of the Ambient Rehabilitation Kit where the lab decontextualized (i.e., with low fidelity prototypes and environment), the field contextualized (i.e., with medium fidelity prototypes and environment), and the showroom enabled users to experience the tangible technologies (i.e., with high fidelity prototypes and environment) (Koskinen et al., 2013). The practice of "lab-field-showroom" approach in this research provides a valuable example for researchers and developers to develop similar technology in the future (see Figure 3-27).

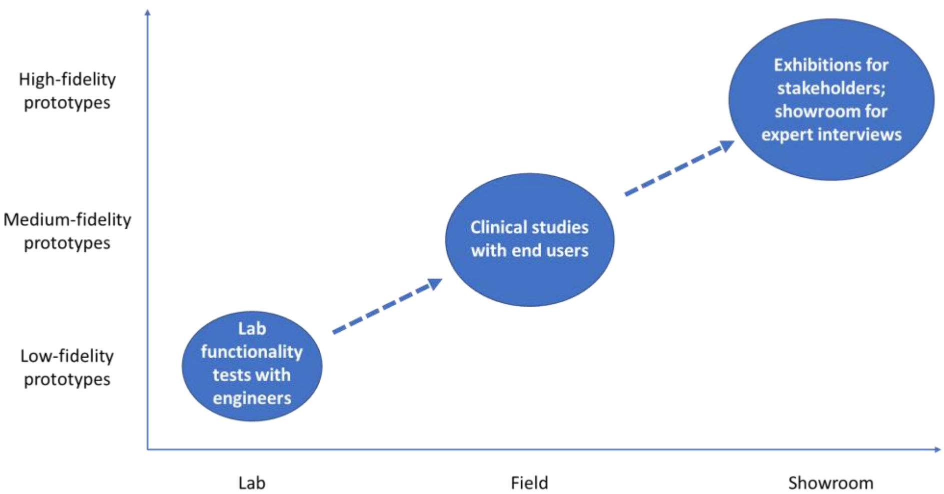


Figure 3-27: "Lab-field-showroom" strategy for testing and exhibitions

3.4.1 Major sensing, monitoring, and analysis functionality testing by engineers (“lab”)

As mentioned in the previous sections, a series of PI^{2}Us are developed in Touchpoint 2. The PI^{2}U prototypes are manufactured, deployed, and tested for main sensing, monitoring, and analysis activities in the laboratory (see Figure 3-28). The qualitative functionality testing of these activities is presented as follows, which clearly demonstrates how various sensors and functions can be integrated into the PI^{2}Us due to their modularity and customizability.

Figure 3-28: The prototypes of various PI^{2}Us (e.g., SilverArc, MiniArc, SilverBed, and iStander) deployed and tested in the laboratory

The ECG sensors, which are embedded in the SilverBed, can provide the medical staff with data regarding the patient’s heart activity during the sleeping period. Additionally, this aspect can support the early detection aspect of the research. Figure 3-29 presents the sensor integration on the SilverBed which produces usable ECG measurement signals in the second image (Figure 3-29 middle). In order to implement such sensors, flexible plastic material was used to improve patient comfort and measurement (Figure 3-29 right). The ECG implementation uses two electrodes to produce more accurate ECG signals (Pehr et al., 2019).

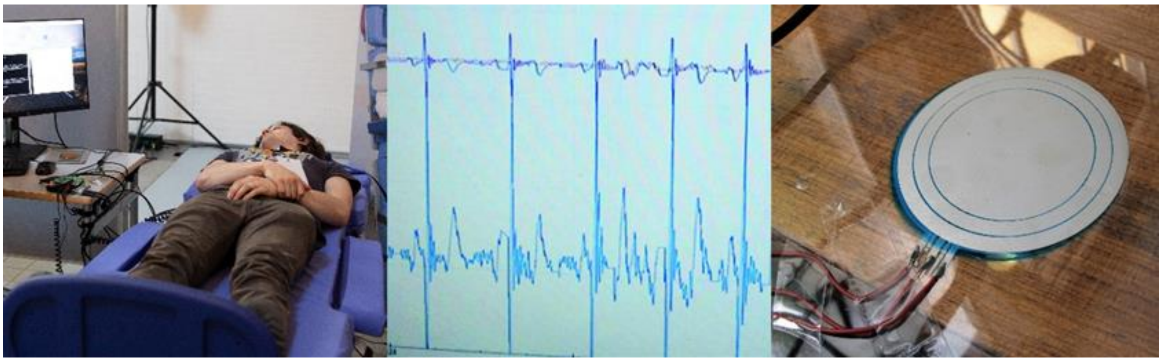


Figure 3-29: Testing of the ECG sensors on the SilverBed

An important issue when considering an immobile patient's care is the prevention and management of pressure ulcers or decubitus. In order to implement the early detection and prevention aspects of the research in the SilverBed, it was decided to integrate a pressure-sensing mattress. This mattress monitors the peak pressure points of a person lying on the bed. Using this data, the Engine can monitor peak pressure points and inform the care personnel for repositioning the patient before they develop decubitus. This sensor provides other functions as well such as breath frequency monitoring mainly for patients sleeping on their abdomens (see Figure 3-30) as well as a micro-mobility monitoring, which are both under implementation. Additionally, the project team is currently exploring the possibility of monitoring heart rate by this sensor.

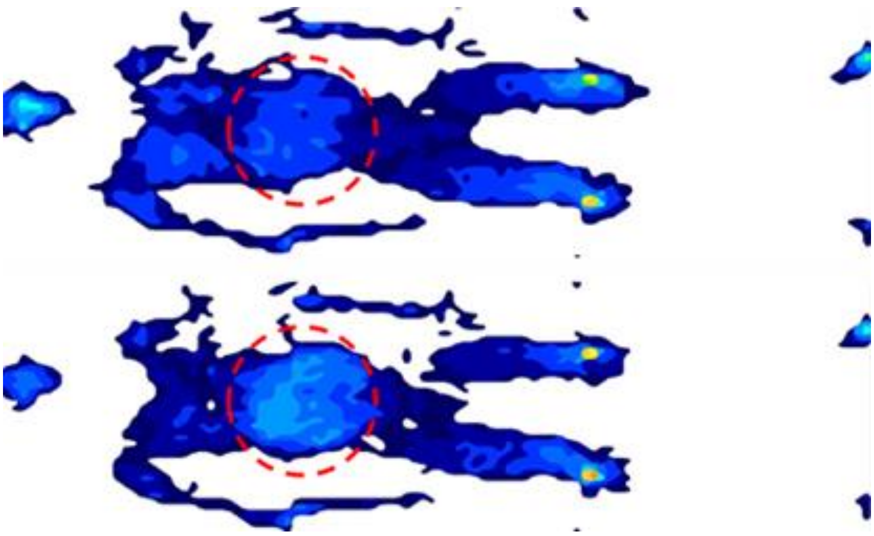


Figure 3-30: Pressure change on diaphragm when inhaling and exhaling (generated by the pressure-sensing mattress)

Using image recognition algorithm, the thermal camera targets two major objectives: 1) breath frequency monitoring over the nostrils during sleep on the back, and 2) body temperature detection/monitoring over the eyes (see Figure 3-31). In the first implementation of these modules in laboratory, the results showed the following: breath frequency monitoring is possible and implemented via the nostrils and that the body temperature monitoring is implemented (monitoring the body temperature via the eyes is, naturally, only possible before the patient goes to sleep). There is a small limitation regarding the implemented prototype: due to the resolution of the current thermal camera, it is only possible to monitor these factors in a range of approximately 50cm distance from the patient’s face. As a result, the thermal camera must either be mounted at the appropriate distance to the face, or the thermal camera must be replaced with a higher quality camera.

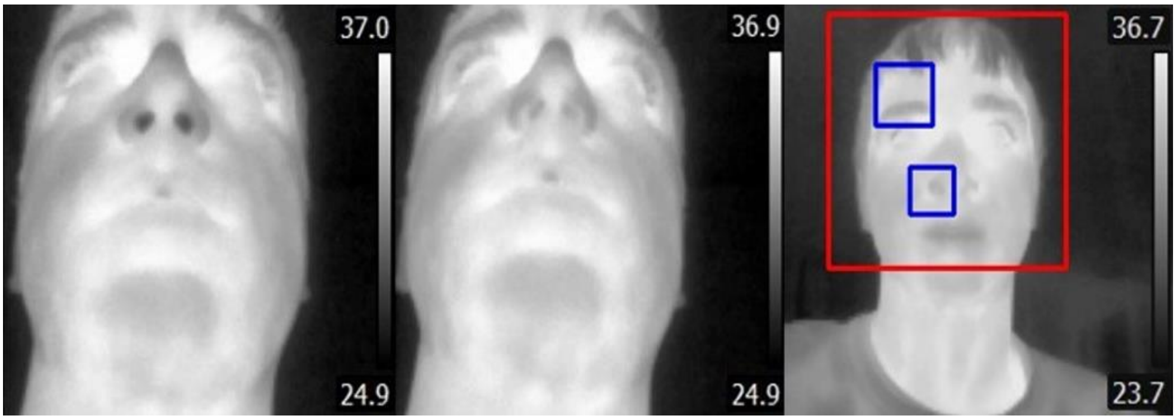


Figure 3-31: Respiration rate monitoring and body temperature measurement over the eyes

The Kinect sensors, integrated into the MiniArc and SilverArc, are used for gesture recognition by considering the hand motions from the user (see Figure 3-32). The Kinect was programmed by using the standard libraries from Microsoft. As the Kinect libraries are not compatible with other operating systems, it is therefore essential to continue with Microsoft Windows as the operating system. The control program of the Kinect gesture recognition was programmed using visual studio and was developed separately from the Graphical User Interface (GUI). Furthermore, the software development of the mounted Kinect on the MiniArc is finalized including the adjustability for recognizing gestures at two different distances (i.e., standing table surface and sitting table surface).

Figure 3-32: User interface and Kinect sensor in the MiniArc

Furthermore, it was also planned to implement an activity sensing system for the Alreh Medical device (see Figure 3-33). This activity sensing system was fused with the current gaming interface of the Alreh Medical device in order to enable lower body interactions with the games. In the first trial, the electromyography (EMG) sensor was implemented and tested. EMG is an electrodiagnostic medicine technique for evaluating and recording the electrical activity produced by the muscles. This was planned to serve as the controller interface for the legs allowing the user to steer a training or rehabilitation game via gestures (e.g., by the Kinect sensor) and leg movements. After the initial implementation and functionality testing in laboratory, the results showed an immense amount of noise when reading the EMG signal both through direct skin contact and over the clothes. This could heavily interfere with the interfacing to the gamification function. As a result, it was decided to consider different approaches for interfacing activity with gamification (e.g., using a touch sensor). Afterwards, such inputs can be used to steer a training or rehabilitation game via foot gestures, which further benefits early detection, monitoring, and activation aspects of the research.

Figure 3-33: Activity monitoring sensors used in the iStander

Therefore, this stand-up counting sensor is developed to partially substitute the EMG sensor mentioned above. Designed and implemented as "battery-based" and "plug-and-play", the stand-up counting sensor is mounted on the Alreh Medical device in a specific way, so that the clinical certificate of the device will not be undermined (see Figure 3-34). This sensor counts the number of “stand-up” events and transfers this count to a local server via a WiFi microchip module (i.e., ESP8266-1, marked in the red circle in Figure 3-34 left). In addition, this sensor is implemented with consideration of its exceptionally low power consumption. With the implemented battery, it can run for more than three months without the need for recharging the battery.

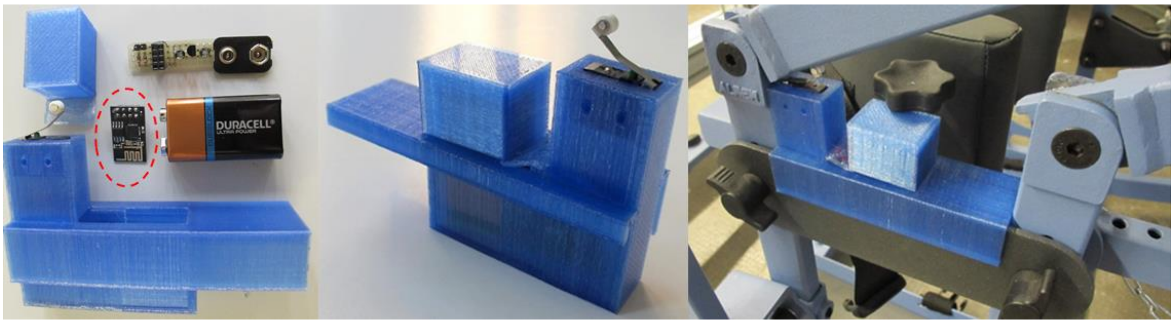


Figure 3-34: Stand-up counter embedded in the iStander

Figure 3-35 shows the algorithm flowchart of the sensor, the stand-up application itself, and their connection. In particular, Figure 3-36 depicts the interface plan of the ESP8266-1 Wi-Fi module, where a 9V battery is used as the power supply regulated by a low-power consumption voltage regulator HT7333. In order to ensure the longevity of the battery, the Wi-Fi module is in a deep-sleep mode most of the time. The Wi-Fi module can be woken up only by a reset, which is executed via the switch. When the Wi-Fi module wakes up, it registers automatically in the Wi-Fi network, and transfers an instant message that is captured by the sever application, which is running on the MiniArc.

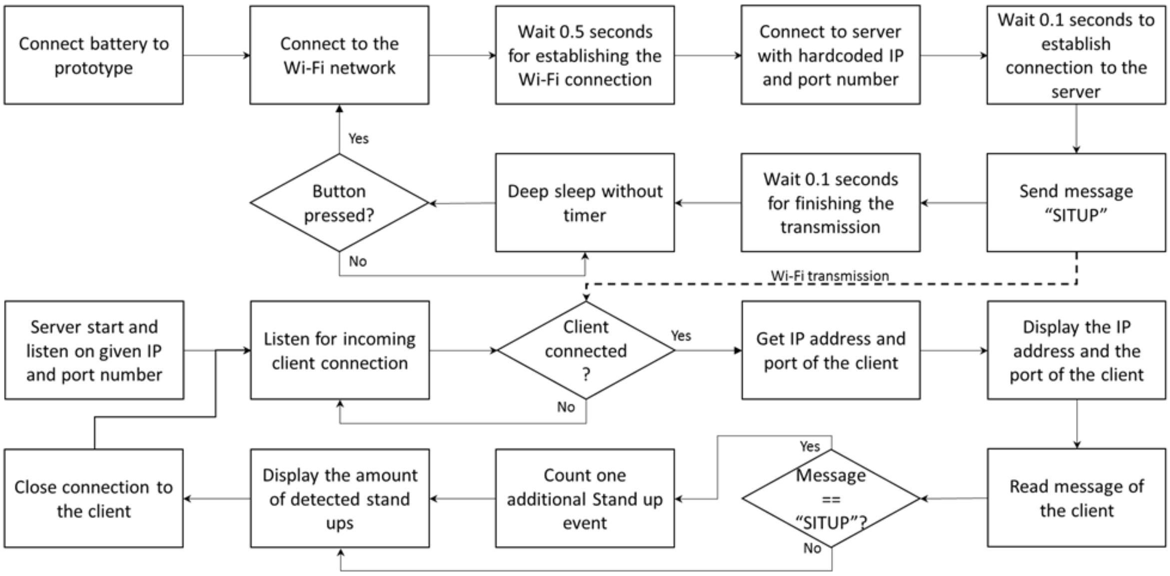


Figure 3-35: The algorithm flowchart of the sensor, the stand-up application itself, and their connection

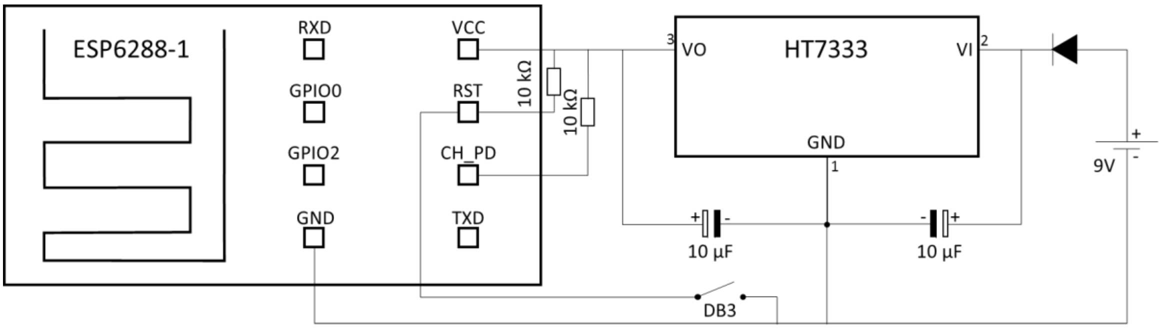


Figure 3-36: The interface plan of the ESP8266-1 Wi-Fi module

Up to now, the overall functionality testing of the PI²Us in the laboratory was successful. Based on the learnings from the testing, the PI²Us will be further revised with more iterations and eventually resemble the proposed furniture design. After the early functionality testing of the prototypes and the first data collection activities, the project team proposed a modularized smart home solution integrating all PI²Us and key technologies in four Touchpoints to create a comprehensive interior living and care environment for older adults. This design shows how the extensive REACH platform can be easily and rapidly tailored to distinct application environments.

3.4.2 Clinical studies using PI²Us in Touchpoint 2 ("field")

While the MiniArc was exhibited outside the laboratory, the evaluation of PI²Us was conducted in various care facility partners. In the REACH project, 30 testing activities (e.g., trials, studies, etc.) have been conducted within the four Touchpoints. All trials conducted in REACH were in conformity with ethical principles set by the Declaration of Helsinki

(Krewer et al., 2020). Data were collected and processed abiding the legal requirements about data protection. All aspects related to the data protection rights of the trial participants were disclosed and explained to them in detail (Schäpers et al., 2020).

In the following sections, several testing activities that are most relevant to the PI²Us developed in Touchpoint 2 are highlighted in order to verify the usability of these devices.

3.4.2.1 Clinical trial at Institute of Cardiology Warsaw: using ActivLife for the rehabilitation of CVD patients

The limited physical activity level of older adults with CVDs leads to the reduction of muscular strength, motion ability, and limb coordination. Consequently, there is demand for implementing novel rehabilitation regimen to improve these physical indicators. Therefore, the aim of this trial was to evaluate the effectiveness, safety, and attractiveness of the training/gaming device and fall protection equipment ActivLife among CVD patients (Krewer et al., 2020).

The trial involved 48 patients who had various CVDs (e.g., post-myocardial infarction, cardiosurgical procedure, heart failure, etc.) who were admitted to the cardiac rehabilitation department of Institute of Cardiology, Warsaw, Poland. All subjects participated in a four-week standardized training program including endurance training and general conditioning exercises.

In addition, 20 of the patients (Group A) were given additional training sessions using the ActivLife Gaming Platforms (five times a week), while the other 28 patients were assigned to the control group. All patients received tests including a strength assessment of lower limbs, a six-minute walk test, and a timed “up and go” test, both before and after the rehabilitation program. They also completed a questionnaire on the use of ActivLife.

As a result, both groups significantly improved in all three tests ($p < 0.05$). The test results of the rehabilitation program can be found in Table 3-5.

Table 3-5: Test results of the rehabilitation program in the trial at Institute of Cardiology, Warsaw

Test	Group A	Control group
Strength assessment of lower limbs (unit: number of repetitions/30s)	11.21 ± 0.61 vs 13.37 ± 3.96	9.96 ± 3.34 vs 13.12 ± 3.99
Six-minute walk test (unit: meters)	369.06 ± 129.1 vs 462.50 ± 104.88	366.53 ± 121.76 vs 457.81 ± 102.2
timed “up and go” test (unit: seconds)	7.74 ± 2.75 vs 6.74 ± 1.8	8.35 ± 2.75 vs 7.27 ± 3.51

In addition, the opinion of Group A subjects towards ActivLife was significantly positive ($p < 0.05$):

- 94.7% of the patients assessed the equipment as “very good”;
- 89.5% of the patients identified it as “comfortable/very comfortable”;
- 100% of the patients found it safe and protective;
- 79.0% of the patients found it useful in reaching their rehabilitation goals;
- 68.4% of the patients thought that it is more attractive than standardized training.

In conclusion, cardiac rehabilitation with the ActivLife Training/Gaming Platform was considered by the CVD patients as comfortable, safe, attractive, and useful in reaching their goals. Objectively speaking, ActivLife is safe and useful for the rehabilitation of CVD patients. Furthermore, although the test results showed improvements for both groups, longer observation and increased training period are needed to evaluate the effectiveness of both types of rehabilitation training.

3.4.2.2 Clinical trial at Schön Klinik Bad Aibling: using iStander to promote mobility

This research was intrigued by a 27-year-old patient admitted to Schön Klinik Bad Aibling who was diagnosed with Guillain-Barré Syndrome for a few months with distal tetraparesis and thus constrained range of motions. The patient was unable to perform sit-to-stand (STS) movement even with therapeutic intervention due to reduced mobility and severe pain to stretch calf muscles. However, with the help of the transfer device iStander developed in the REACH project, the STS movement was made possible, and the STS training was realized. Inspired by the case, this trial aimed at analyzing the differences and potential benefits of the STS task with iStander compared to standing up without the device. In particular, the biomechanics and the range of motion in the ankle joint during the STS transition were observed. A 3D-motion analysis using Simi Reality Motion Systems (www.simi.com) was conducted with five healthy volunteers executing 10 STS movements with and without iStander. The movements of their ankle, knee, and hip joints in the sagittal plane were analyzed using marker’s data via Matlab. The results show that STS movements from a chair causes more extension in the ankle joints, and more flexion in the knee and hip joints compared to those using the iStander.

In conclusion, the result of a smaller needed range of motion in the ankle using iStander explains the clinical finding why the patient was able to perform STS movements while having less pain during the training with the device. One of the main goals of the REACH project is to promote activity and independence of older adults aged 65 and over. Age-associated deteriorations in the ankle joints make ADLs such (e.g., STS) challenging for them. However, this analysis shows that a transfer device like iStander could be useful not only for older adults, but also for users with limited range of motion (Steinböck et al., 2019).

3.4.3 Exhibitions and expert interviews (“showroom”)

During the REACH project, the smart furniture was displayed in several exhibitions and trade fairs, which is an important and effective approach to disseminate the products due to its personal communication element (Kellezi, 2014). Hence, two of the exhibition activities are briefly reported as follows. In addition, an expert interview was conducted in the simulated home environment at TUM, which is another effective qualitative research method to improve the future iteration of the abovementioned PI^2U prototypes (Döringer, 2021).

3.4.3.1 Exhibition at Pinakothek der Moderne

October 26th, 2018 marked the debut of the PI^2Us. On that day, the TUM team presented the smart furniture MiniArc at the inauguration ceremony and exhibition of the "Munich School of Robotics and Machine Intelligence" (MSRM; www.msrm.tum.de) at the museum Pinakothek der Moderne in Munich. The MiniArc successfully attracted the visitors' interests. At the same time, the project REACH was promoted to visitors of both the MRSM exhibition and the museum (see Figure 3-37).

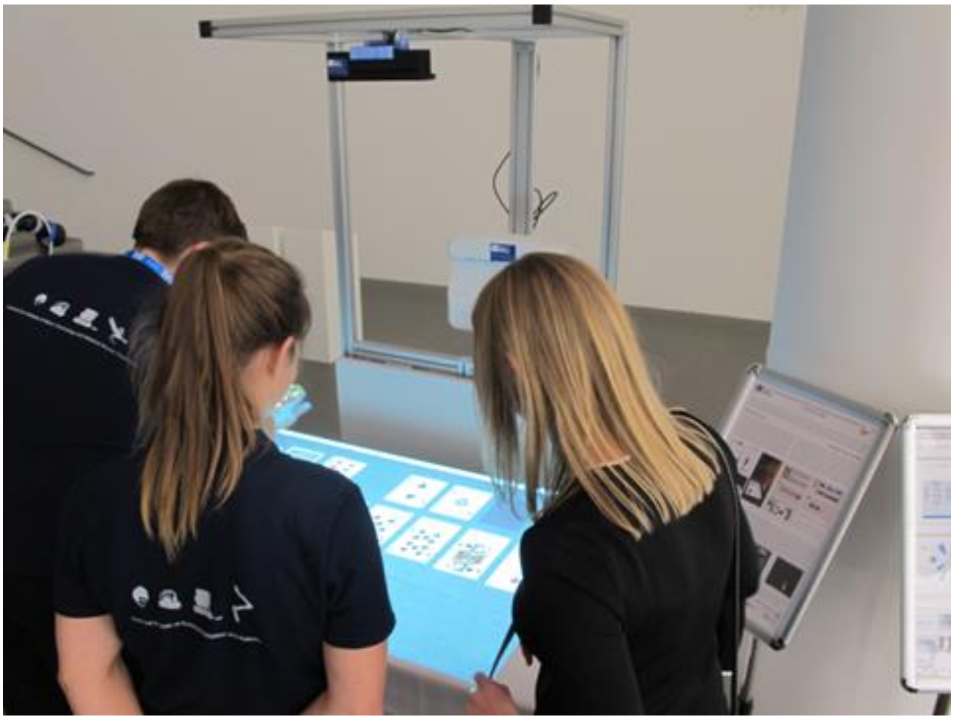


Figure 3-37: Exhibition of MiniArc in Pinakothek der Moderne in Munich (photo: J. Güttler)

Overall, the demonstration provided valuable feedback regarding the reliability of the MiniArc. For example, while the MiniArc was being transported, a joint loosened, which lead to a decalibration of the Kinect and thereby the gesture recognition of the MiniArc. On the software level, two further bugs were found by the testers, when they tried to give a multi-touch input. Furthermore, the feedback regarding usability and acceptance of the product was positive, and most testers claimed that they could imagine themselves using such an application at home.

3.4.3.2 Exhibition at Lyngby (simulated community care home environment and hospital environment)

The abovementioned Ambient Rehabilitation Kit concept played a major role during the exhibition session at the Conference on Active and Healthy Ageing 2019 at DTU, Lyngby, Denmark, which is one of the use case settings in REACH (Andersen and Ehrari, 2019). Technologies developed in REACH were highlighted in the center of the exhibition, along with many other health technology developers, suppliers, and service providers from Denmark and beyond, to showcase their solutions in Oticon Hall at DTU. Based on the Ambient Rehabilitation Kit concept, the project team proposed an integrated two-room solution respectively representing community and hospital care environments. The plan was sent to DTU administration for fire safety review and was approved after minor revisions. The exhibition was divided into two main parts: 1) community care environment, and 2) hospital and rehabilitation care environment. The detailed exhibition and demonstration plan is shown below (see Figure 3-38), as is a list of various technologies presented in these two contexts (see Table 3-6).

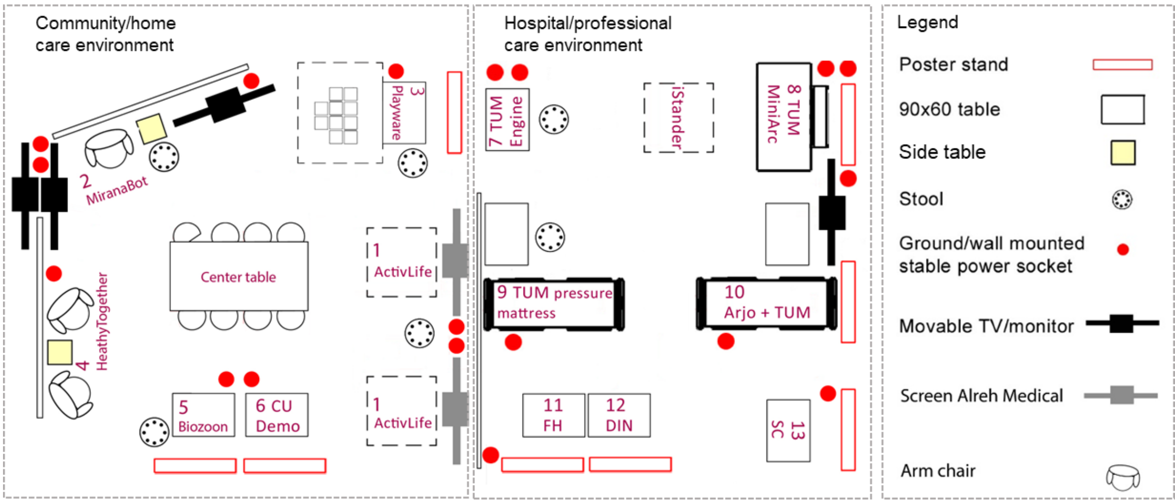


Figure 3-38: Proposed REACH exhibition and demonstration plan

Table 3-6: List of various technologies presented in the REACH exhibition

Number	Environment	Technology in the REACH exhibition
1	Community/ home care environment	ActivLife rehabilitation device for seniors, Alreh Medical
2		MiranaBot, Geneva University Hospitals
3		Moto Tiles, Technical University of Denmark
4		HealthyTogether app, Eindhoven University of Technology
5		Personalized & 3D food printer, Biozoon
6		Activity trackers showcasing, University of Copenhagen
7	Hospital/ professional care	CARP Platform in REACH Engine, Technical University of Munich
8		MiniArc, Technical University of Munich
9		SilverBed (pressure mapping), Technical University of Munich

10	environment	SilverBed (Sara Combilizer), Technical University of Munich + Arjo
11		Activity recognition demonstration, Fraunhofer IAIS
12		Standardization within REACH, Deutsches Institut für Normung
13		Medical-grade wearable demonstration, SmartCardia

Due to the application of the Ambient Rehabilitation Kit concept, the project team was able to use only one day before the exhibition to set up the two care environments and the relevant PI^2Us efficiently without any obstacles. On the exhibition day, the listed technologies were demonstrated to visitors (including but not limited to local older residents, scholars, EU officials, and entrepreneurs) during the event (see Figure 3-39, Figure 3-40, and Figure 3-41). In general, the exhibition received positive reactions and feedback from the visitors and top researchers which further validated the effectiveness of the proposed concept in this research. The experience gained during the process can be further used to perform similar application in other contexts, as well as to refine and improve the technologies in the next developing phase. For example, it was learned from the exhibition that the respiration rate monitoring system on the MiniArc can be affected by the complexity of the background. As a result, the sensitivity of the image recognition function was not as high as that in the laboratory. To improve the sensitivity, further training of the machine learning algorithm with different backgrounds is needed. In summary, the exhibition can be considered as one successful application of the customization and materialization of the Ambient Rehabilitation Kit concept based on the PI^2Us.

Figure 3-39: Aerial view of the REACH exhibition venue that more than 200 people attended

Figure 3-40: The Ambient Rehabilitation Kit at community/ home care setting

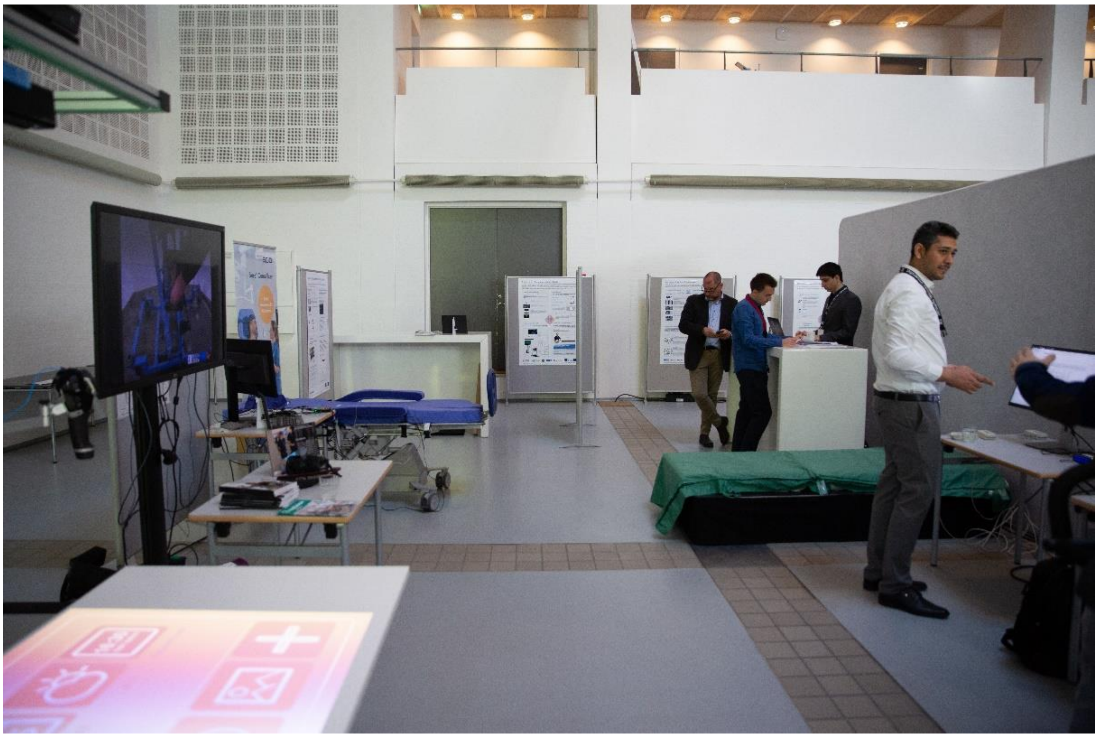


Figure 3-41: The Ambient Rehabilitation Kit at hospital setting

3.4.3.3 Expert interview in simulated home environment

Expert interview is an effective qualitative research method that has been widely used in social research in the recent decades (Döringer, 2021). The proposed Ambient Rehabilitation Kit mainly consists of three major realms which are design, engineering, and medicine. Therefore, the author invited five experts in old age from the related industries (e.g., engineering, fashion, healthcare, business, education) to TUM's testing apartment to experience and evaluate the Ambient Rehabilitation Kit. Each of them tested the PI^{2}Us (e.g., MiniArc/SilverArc, SilverBed, iStander, ActivLife) thoroughly for approximately one hour in a simulated home environment. After the test, they were asked to answer a short questionnaire to understand their opinions and attitudes towards the PI^{2}Us. Their responses that were anonymized as requested in order to protect their privacy are recorded and analyzed below.

Expert A Mrs. D (aged over 80 years old) is a senior fashion designer who holds degree in history of arts at Ludwig Maximilian University of Munich. She created and has been running a high-end hand-knitted clothing company in Bavaria, Germany since 1979.

Expert B Dr. S (aged over 70 years old) is a senior engineer and retired executive at a major German aircraft engine manufacturer. He has more than 40 years of experience in technology and innovation, and now works as a freelance consultant for innovation management since 2016.

Expert C Dr. L (aged over 65 years old) is a medical doctor (general practitioner) who founded a modern medical care center in a small city in Baden-Württemberg, Germany since 2016. He is internationally recognized as an expert in the field of micronutrients and has trained several thousand people in this field.

Expert D Ms. L (aged over 60 years old) is general manager of a medical care center in Germany since 1984. As a business economist, she successfully founded two companies, and currently serves on the board of directors of a health supplements manufacturer.

Expert E Ms. S (aged over 65 years old) is a high school educator for physical education with over 40 years of teaching experience. Her opinion is valuable because she is not only an experienced physical education teacher, but also an older adult herself.

Some of the photos during the testing process with the experts can be found in Figure 3-42 (the experts provided written consent to use their photos anonymously). Their responses of the interview after the showroom experience are summarized in Table 3-7.

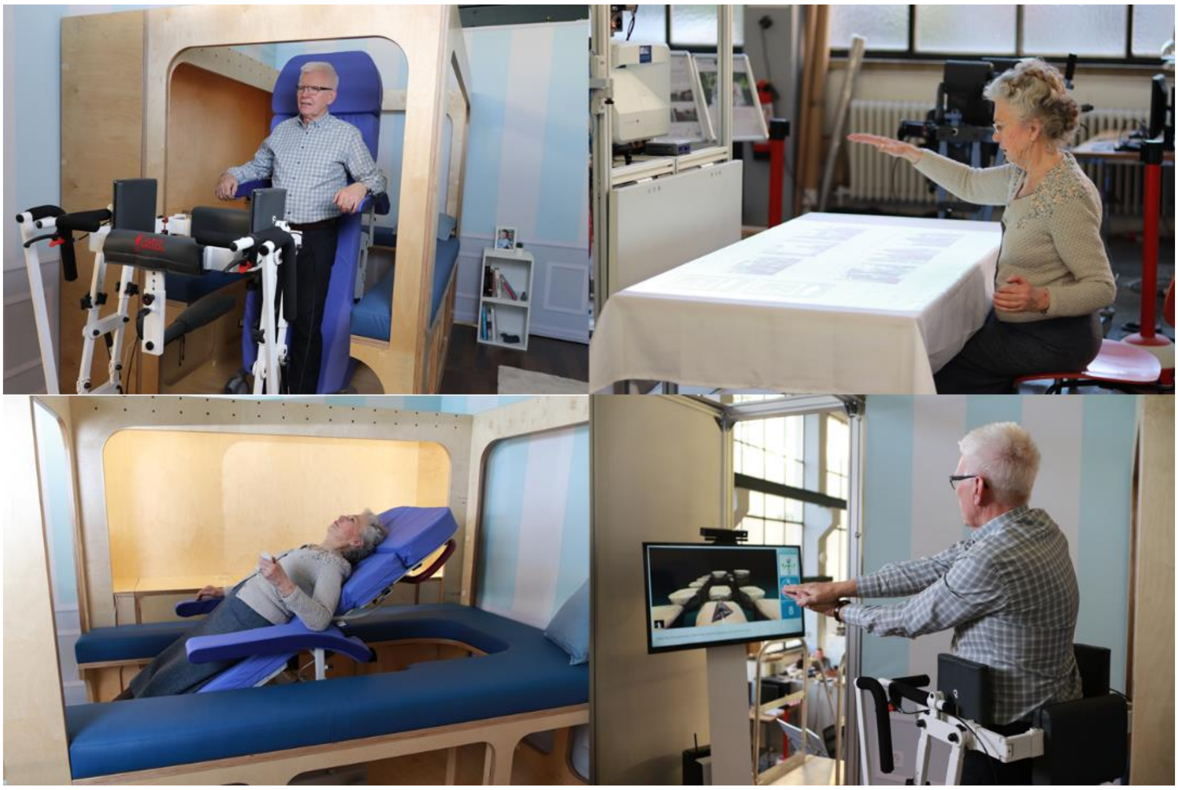


Figure 3-42: Testing process with the experts in simulated home environment ("showroom") at TUM

Table 3-7: Opinion questionnaire responses of the experts

No	Question	Answer	Expert A	Expert B	Expert C	Expert D	Expert E
1	What is your overall opinion towards elderly-oriented smart furniture technology?	1) Very negative 2) Negative 3) Neutral 4) Positive 5) Very positive	1) 2) 3) 4) 5) ✓	1) 2) 3) 4) 5) ✓	1) 2) 3) 4) 5) ✓	1) 2) 3) 4) 5) ✓	1) 2) 3) 4) 5) ✓
2	Please rate the importance of the listed attributes in elderly-oriented	1) Quality 2) Affordability 3) Good look 4) Ease of use	1) 5 2) 4 3) 4 4) 5 5) 4	1) 5 2) 4 3) 4 4) 5 5) 4	1) 5 2) 4 3) 5 4) 5 5) 4	1) 5 2) 5 3) 4 4) 4 5) 4	1) 5 2) 5 3) 3 4) 5 5) 4

	smart furniture in general (1 means very unimportant and 5 means very important).	5) Multifunctionality 6) Safety 7) Privacy protection	6) 5 7) 3	6) 5 7) 5	6) 5 7) 5	6) 5 7) 5	6) 5 7) 5
3	Can you imagine to use elderly-oriented smart furniture in your own home soon?	1) Yes 2) No	1) ✓ 2)	1) ✓ 2)	1) ✓ 2)	1) ✓ 2)	1) ✓ 2)
4	Please rate how useful is MiniArc/SilverArc.	1) Very useless 2) Useless 3) Average 4) Useful 5) Very useful	1) 2) 3) 4) 5) ✓	1) 2) 3) 4) ✓ 5)	1) 2) 3) 4) 5) ✓	1) 2) 3) 4) 5) ✓	1) 2) 3) 4) ✓ 5)
5	Please rate how useful is ActivLife.	1) Very useless 2) Useless 3) Average 4) Useful 5) Very useful	1) 2) 3) 4) ✓ 5)	1) 2) 3) 4) 5) ✓	1) 2) 3) 4) 5) ✓	1) 2) 3) 4) 5) ✓	1) 2) 3) 4) 5) ✓
6	Please rate how useful is iStander.	1) Very useless 2) Useless 3) Average 4) Useful 5) Very useful	1) 2) 3) 4) 5) ✓	1) 2) 3) 4) ✓ 5)	1) 2) 3) 4) 5) ✓	1) 2) 3) 4) 5) ✓	1) 2) 3) 4) ✓ 5)
7	Please rate how useful is SilverBed.	1) Very useless 2) Useless 3) Average 4) Useful 5) Very useful	1) 2) 3) 4) 5) ✓	1) 2) 3) 4) 5) ✓	1) 2) 3) 4) 5) ✓	1) 2) 3) 4) ✓ 5)	1) 2) 3) 4) ✓ 5)
8	What do you think are the shortcomings of these elderly-oriented smart furniture?		They take up so much space.	• MiniArc: gestures are limited to people with good mobility • iStander: not easy enough to use			• Affordability • Space at home
9	What other functions would you like to add to elderly-oriented smart furniture?		MiniArc/ SilverArc could include radio stations plus information about their programs.	• Safety features for SilverBed • Smart robotic features for iStander			
10	In your opinion, what is the future market potential of elderly-oriented smart	1) Very small 2) Small 3) Average 4) Big 5) Very big	1) 2) 3) 4) ✓ 5)	1) 2) 3) 4) ✓ 5)	1) 2) 3) 4) ✓ 5)	1) 2) 3) 4) ✓ 5)	1) 2) 3) 4) ✓ 5)

	furniture technology?						

In summary, after experiencing the PI^2Us, all five experts had highly positive opinion towards the elderly-oriented smart furniture technology. At the same time, all of them could imagine using these devices in their own home in the future. In particular, all of them considered the five prototypes (e.g., MiniArc, SilverArc, ActivLife, iStander, SilverBed) either useful or very useful. Furthermore, all of the five experts thought that there will be a big market potential of elderly-oriented smart furniture technology. As a result, the experts from the related fields (e.g., engineering, fashion, healthcare, business, education) all had highly favorable opinion towards the prototypes in the showroom, which established a strong endorsement to the Ambient Rehabilitation Kit.

Regarding the shortcomings of these prototypes, Expert A and E thought that they take up too much space for home environment. Also, Expert A expressed her dissatisfaction with the MiniArc/SilverArc that they could include radio functions as well as information about their programs. Expert B expressed some difficulties in using iStander and maneuvering the interface of MiniArc by gesture. He also expressed the wish to add safety measures to SilverBed. In addition, Expert E expressed her concern for the affordability of the technology. As a result, the following lessens can be learned to further improve the PI^2Us in the next development cycle:

1) The volume and weight of the prototypes shall be further reduced.
2) Classic functions that are familiar to older adults such as a radio module as well as information about its programs shall be integrated into the GUI of the MiniArc and SilverArc.
3) The algorithm of the GUI of MiniArc and SilverArc needs to be further optimized to enhance the user experience of gesture maneuver.
4) The ergonomics of iStander and SilverBed can be further improved.
5) The costs of the PI^2Us shall be considered and optimized to improve affordability.

3.5 Discussion

In this chapter, a service system transforming clinical and care environments into personalized modular sensing, prevention, and intervention systems was proposed, encouraging older adults to become healthier through various activities. To achieve that goal, a series of smart interior devices integrating advanced sensing and assistive technology, namely PI^2Us, were developed which seamlessly materialize the care concepts and functionality. Meanwhile, a flexible modular Ambient Rehabilitation Kit integrating abovementioned assistive technologies was proposed to create a unique interior living and care solution for older adults in various living environments.

The Ambient Rehabilitation Kit also includes a strategy for testing and exhibiting the developed technologies. Accordingly, a series of testing and exhibition activities from lab, field, and showroom were reported in line with the strategy, which gained solid evidence for the main RQ (i.e., how efficient can the novel research field of Ambient Assisted Living help mitigate the crisis of population aging by increasing older adults' activity and independence level?) and constructive feedback on how to improve the system further. In particular, this chapter answers SQ2 (i.e., what are the main components and functions of the proposed system?).

As the next step, a framework for economic evaluation using automated solutions such as the PI^2Us applied in different care environment (e.g., home, hospital, care home) will be proposed to verify marketability of the solutions as well as to convince potential stakeholders and investors. Detailed insights regarding this aspect will be revealed in the next chapter.

4 To invest or not to invest? A framework for the cost-benefit analysis of robotic and automated systems (Check)[6][7]

“Other people want to make friends; I just want to make you money.”

Jim Cramer[8]

No matter how advanced and efficient an innovation is, if it cannot achieve profitability, it will not be successful due to the lack of investment motivation. Therefore, this chapter aims at developing a simple framework for the economic evaluation of robotic and automated systems in the architecture, engineering, and construction (AEC) sector, and the healthcare industry. The versatility and effectiveness of the framework will be verified successively with two case studies, 1) a cable-driven facade installation robot, and 2) the smart furniture solution based on PI^{2}Us proposed in the chapter above, which both share the similarity of using robotic and automated technologies to supplement the labor shortages in their respective sectors.

Ever since the first debut in the 1970s in Japan, single-task construction robots (STCRs) have become a worldwide research and development topic. They are robots or automated devices that are developed primarily for tasks on the construction sites (Cousineau and Miura, 1998). It is a highly cross-disciplinary field which requires an integration of a variety of knowledge and expertise such as civil engineering, architecture, industrial design, construction management, robotics, mechanical engineering, electrical engineering, and informatics.

Today, the application fields of STCRs continue to expand. For instance, Bock and Linner summarized 200 existing STCR systems into 24 categories based on their functions (Bock and Linner, 2016a). However, currently, there is still a gap in the ubiquitous application of STCRs for onsite construction due to various reasons, such as insufficient proof of net

[6] This chapter is partially based on the methodology of the research article entitled “A Simple Framework for the Cost–Benefit Analysis of Single-Task Construction Robots Based on a Case Study of a Cable-Driven Facade Installation Robot” (Hu et al., 2021a) published in Buildings, Volume 11, Issue 1, and has been adapted and reused here with the permission of the publisher, see appendices. The authors retain the copyright of this publication according to the publisher (see Appendix IV: Letters/statements of reuse permission from publishers). Authors’ contribution: R. Hu (correspondence, conceptualization, methodology, formal analysis, investigation, data curation, visualization, writing-original draft preparation, writing-review and editing), K. Iturralde (conceptualization, methodology, investigation, data curation, visualization), T. Linner (conceptualization, methodology, writing-review and editing), C. Zhao (methodology, writing-review and editing), W. Pan (conceptualization), A. Pracucci (data curation), and T. Bock (conceptualization, supervision).

[7] This research received funding both from the European Union’s Horizon 2020 research and innovation programme under grant agreement No 732513, and from the European Union’s Horizon 2020 research and innovation programme under grant agreement No 690425.

[8] Jim Cramer (1955-): American TV show host and former hedge fund manager.

economic benefits, lack of modularity in building components, lack of skilled labor for operation, incompatibility with other construction tasks, and time-consuming onsite setup (Bock and Linner, 2016a). Therefore, more research evidence is needed to prove the net economic benefit of the STCRs, compared to traditional construction methods, in order to boost the speed and breadth of the implementation of STCRs.

Cost–benefit analysis (CBA) is oftentimes considered as one of the most important problem-solving tools in decision-making processes, yet there is a lack of research on the quantitative evaluation of STCR systems to study their economic implications for key stakeholders. This chapter aims to propose a simple methodological framework for the cost-benefit estimation of robotic and automated systems based on the case study of the onsite cable-driven facade installation robot developed in the EU research project named Hephaestus.

Cost-benefit analysis (CBA) is commonly used for economic evaluation of a project or policy. It can be dated back to the mid-19th century by French engineer and economist Jules Dupuit (Fodor, 2012). It is a policy assessment tool that monetizes all impacts of a project or policy to all relevant stakeholders in society (Boardman et al., 2018). According to Munger, CBA is considered as the "single most important problem-solving tool in policy work" (Munger, 2000). The CBA usually can be divided into several major steps in order to make the process more manageable. The steps can usually be described as follows (Boardman et al., 2018).

(1) Specify the set of alternatives projects.

(2) Decide who will be the key stakeholder for the benefits and costs.

(3) List impacts and determine ways to measure them.

(4) Predict impacts quantitatively over the life of the project.

(5) Monetize every impact.

(6) Discount benefits and costs to obtain present values.

(7) Calculate the net present value of each alternative.

(8) Perform sensitivity analysis.

(9) Make a recommendation.

Like every assessment tool, CBA has certain limitations, such as its imperfect process, its monetization of non-market articles, the openness of the results, the thorough examination by the public, its dependence on correctness and completeness, the difficulty of being understood, its ethics, and its neglect of long-term environmental impacts (Boardman et al., 2018). Nevertheless, considering its wide usage in the policy-making activities, it is naturally reasonable to apply CBA as a tool to evaluate the economic benefits and costs of STCR systems in the AEC industry.

4.1 Literature review

With regard to the construction industry, there have been several instances of CBA research available to the public. In particular, Shen et al. compared the costs and benefits of prefabricated public housing projects and traditional housing projects based on survey and field research (Shen et al., 2019). The research reported an analysis of construction costs and environmental benefits of prefabricated housing, largely based on collected questionnaires from more than 50 managers, which takes a great amount of work. Li and Mandanu proposed an uncertainty-based methodology for the life-cycle CBA of highway projects that handles certainty, risk, and uncertainty (Li and Madanu, 2009), which requires accessing a large amount of historical data. In addition, Medici and Lorenzini proposed a mathematical model for optimizing energy-saving measures on the building envelope, which reveals the relationship between energy benefit and the related cost (Medici and Lorenzini, 2014). With regard to construction automation, back in 1988, Skibniewski and Hendrickson conducted a cost-benefit estimation on a robotic on-site surface finishing system (Skibniewski and Hendrickson, 1988). However, the work was based on a proposed design and cost estimations, which could not be verified at that time. Later, Jang and Skibniewski also conducted a CBA of an embedded sensing system for construction material tracking, compared to manual materials tracking, method based on interviewing the experts regarding labor productivity (Jang and Skibniewski, 2009). Another interesting research by García de Soto et al. compared the productivity of robot fabrication to that of manual technique in building complex concrete walls (García de Soto et al., 2018), but, strictly speaking, it is a cost and time analysis rather than a comprehensive CBA. Furthermore, Kim et al. developed an assessment tool to evaluate the economic efficiency of an integrated automated onsite construction system (Kim et al., 2010), focusing on assessing an integrated automated construction system rather than a specific STCR.

These precedents provide insightful knowledge of economic evaluation for the construction sector. However, few of these methods are specifically designed for conducting the CBA of STCR systems, due to the lack of accumulated information in practical applications of construction robots, even though the research field of STCR systems is becoming more popular in recent years.

Therefore, developing a practical method of CBA for evaluating STCR systems would be beneficial to both academia and industry. The goal of this research is to explore a simple framework for the cost–benefit analysis of STCRs, compared to conventional methods, which can be quickly adapted and used for evaluating other STCR systems. The framework will be verified in the case study of onsite facade installation performed by the cable-driven robot developed in the Hephaestus project. The results of the case study can help determine whether the Hephaestus robot is worth investing in for construction companies. More importantly, this framework can be easily adapted to evaluate other STCR systems in various contexts. Furthermore, the results can provide evidence for the policy makers to decide how many resources shall be allocated or invested to the research and development of automated construction technologies.

4.2 Methods

As mentioned above, this research aims at proposing a simplified method for performing the economic evaluation for construction robots. In this section, the analytical framework and cash flow analysis table for calculation are proposed in general, which, later, is applied to the case study thereafter.

4.2.1 Analytical framework for the CBA

In order to compare the STCR solutions to the conventional construction methods, the following simple and practical analytical framework for CBA is proposed (see Figure 4-1). The CBA in this article will follow this analytical framework.

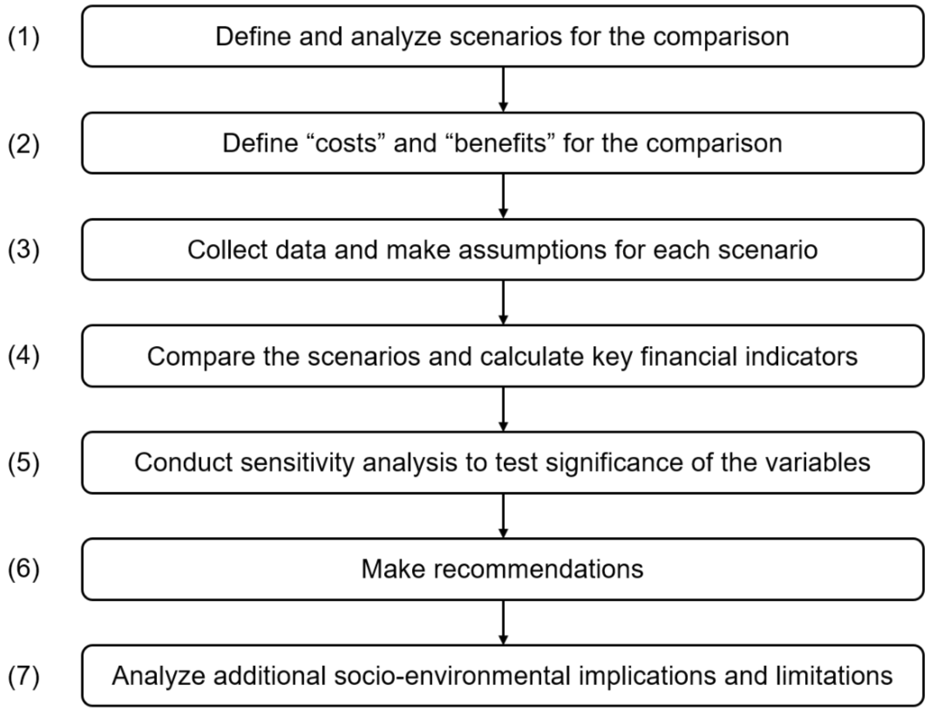


Figure 4-1: The analytical framework of cost–benefit analysis (CBA) applied in this research

4.2.2 Cash flow analysis table

In the calculation process of the CBA, all relevant factors that affect the main stakeholder need to be considered. Normally, the cash flow analyses for CBA range from at least three (small-scale projects) to more than ten years (e.g., large-scale public projects) (Jones et al., 2014; Li and Madanu, 2009; Wang et al., 2014). The five-year calculation period here is mainly because the engineering partners in the project estimate that the lifecycle of such types of construction robots will likely be approximately five years. More importantly, for individual companies as the key beneficiaries, the investment will not be attractive for them if the payback period is longer than five years (e.g., 10 years or above). Therefore, five years is a reasonable time horizon for economic evaluations of STCRs. As a result, a comparison table between conventional methods and STCR solutions is designed which takes every factor during the onsite construction task into consideration in a five-year period (see Table 4-1).

Table 4-1: Template of the cash flow analysis table

Cashflow analysis to compare novel STCR solution and conventional method								
Key stakeholder/beneficiary							Operating region	
Cash outflows	Year 1	Year 2	Year 3	Year 4	Year 5	Total (€)	Explanation and remarks	
Central - hardware costs								
Central - software costs								
Central - network costs								
Central - utility costs								
Central - operation								
Central - maintenance								
Central - other								
Per robot costs - hardware								
Per robot costs - software								
Per robot costs - network & utility								
Per robot costs - training								
Per robot costs - transport								
Per robot costs - installation								
Per robot costs - operation								
Per robot costs - disassembly								
Per robot - maintenance								
Per robot - other								
Total outflow								
Savings - equipment								
Savings - labor								
Savings - utility								
Savings - operational								
Savings - maintenance								
Savings - other								
Total savings								
Net annual cashflow								
Net cumulative cashflow								
Coefficient of productivity								
Annual wage increase								

In this template, the light grey cells indicate the cost and saving aspects that need to be taken into consideration, whereas the white cells are used to input values for each cost and saving aspect in the respective year. Each line of item is followed by an “explanation and remarks” cell to describe the respective item in detail (e.g., explanation, calculation, additional information, etc.)

In particular, in the cash outflow category, the “central” rows indicate the indirect costs that a construction company needs to bear in their headquarters in order to run each robot system for a specific task each year, whereas “per robot costs” rows indicate the direct costs of each robot system each year. The “savings” rows indicate the costs of conventional construction method to conduct the same task each year. The “explanations and remarks” row can be used to explain how each row is calculated. If by, or before, year 5 the net cumulative cash flow turns from negative to positive, it suggests that the STCR system is likely to be worth investing in. Furthermore, based on the result of this table, key financial indicators can be calculated accordingly.

In the next section, a case study of an STCR project for facade installation is conducted, and a CBA of the STCR system is performed, based on the proposed framework, in order to verify the method.

4.3 Case Study I: Cable-driven facade installation robot

After the comparison framework is defined, a case study comparing the conventional curtain wall installation method and the alternative Hephaestus cable robot solution is conducted, as follows.

4.3.1 Curtain wall installation process

A curtain wall is an exterior envelope of the building that does not carry any vertical loads of the roof or floor. It supports its own weight as well as other imposed loads, such as wind, and transfers these forces to the building structure. It provides benefits such as daylight shading, insulation, and weight reduction (Herzog et al., 2017). Usually there are two types of curtain wall installations: (1) the stick system, where the assembly of the curtain wall components such as frames and glass panes, takes place on site; (2) the unitized modular system, where the prefabricated curtain wall modules (CWMs) are installed onsite. Due to the scope of this research, only the unitized prefabricated module system is considered. The standard CWM installation consists of four main steps, which are (1) bracket installation, (2) lifting the CWM, (3) CWM installation with position adjustment, and (4) CWM unit fixation (see Figure 4-3) (Taghavi et al., 2018).

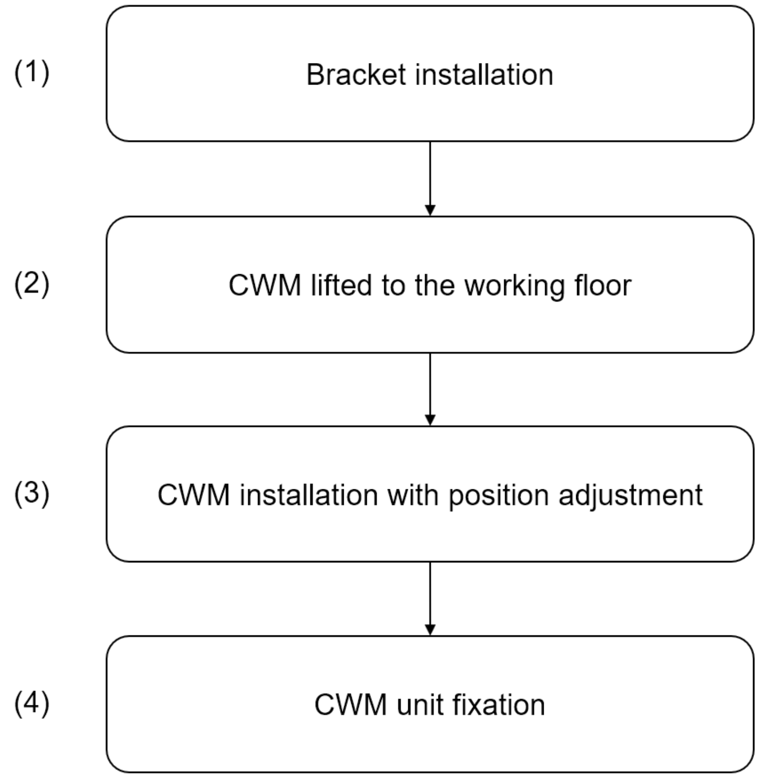


Figure 4-2: Four main steps in the curtain wall module (CWM) installation

4.3.2 Conventional CWM installation

In the first step of installation, the brackets will be manually installed to the building floors. There are two main techniques for bracket installation: the cast-in channel technique and the drilling technique. In the cast-in channel technique, the channels are welded onto the rebars of the framework before pouring the concrete, whereas the drilling technique requires drilling holes based on pre-measured drilling points which avoid rebars underneath. In the context of this research, only the drilling technique is involved. During the bracket installation process, the position of the CWM will be checked and controlled by using measurement systems such as a total station. The placement of the brackets is critical and will likely not be readjusted later. In the meantime, the modules will be transported to the construction site and stored after being unpacked and assembled. In the second step, the CWM will be lifted by the crane to the working floor (or, alternatively, in some cases, be elevated to the working floor through an elevator if possible). In the third step, while the crane holds the weight of the CWM, workers on the working floor minutely adjust the position of the CWM to ensure its installation to the brackets. Finally, after the position of the CWM is correctly confirmed, workers on the working floor fix the unit and the next CWM installation starts (see Figure 4-3) (Taghavi et al., 2018).

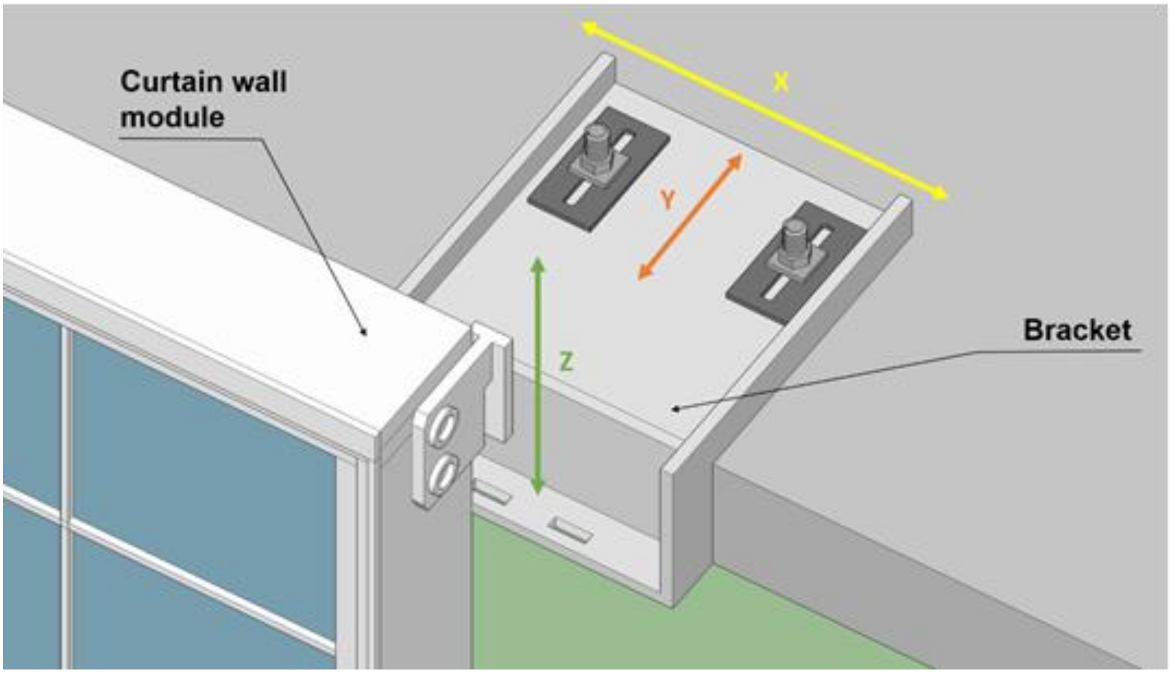


Figure 4-3: Schematic diagram of a typical bracket on the concrete building floor and its connection with a CWM module (the drilling technique)

Therefore, in the conventional CWM installation process, all the four steps are done manually by workers with the help of certain machines. The installation of brackets is completed by workers one by one manually, which is highly time-consuming. As demonstrated in Figure 4-4, the manual method normally involves several workers to work together at height, creating high labor costs and potential danger for these workers (e.g., injuries caused by machinery, back injuries from heavy lifting, falls from height, hearing loss from long-term exposure to loud machinery, etc.). In addition, workers on the ground, for component handling, and a tower crane, for CWM positioning, are necessary as well.

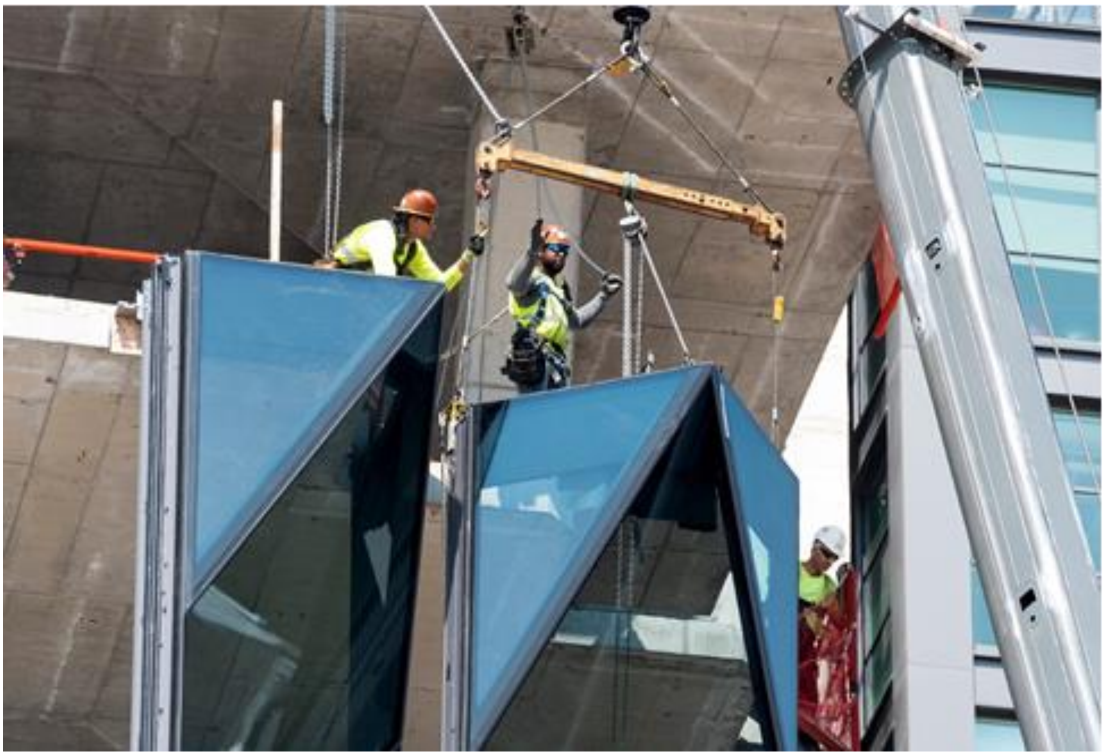


Figure 4-4: Several workers working at height during the CWM installation process (facade installation in Solar Carve Tower, New York. Facade engineered and manufactured by Focchi Group; photo by Timothy Schenck).

4.3.3 Automated CWM installation

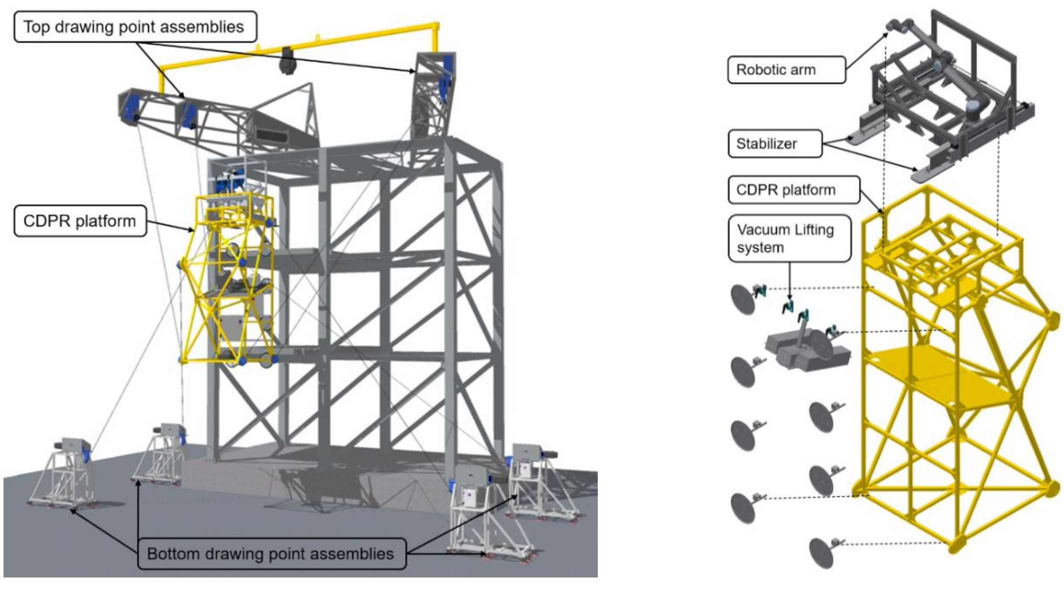
There are several existing instances of automated curtain wall installation. For example, a patented method developed by Brunkeberg Systems AB uses a dedicated railing system to automatically install specially-designed CWMs from the outside of a building (Falk and Augustinson, 2015). However, the railing installation process is manual, and might not apply to certain types of buildings. Other researchers reported a mobile robot that can perform facade installation from the inside of the building, but it only managed to automate the third step, which is positioning the CWM. Činkelj et al. developed a hydraulic telescopic system that installs facade panels to the building from the outside. However, this semi-automated, tele-operated system is specialized for handling facade panels rather than CWMs, and there is also a height limitation due to the use of a telescopic handler (Činkelj et al., 2010). In addition, re-searchers also proposed other novel solutions for the automatic installation of the facade, but many are still at conceptual level (Ferravante et al., 2019; Iturralde et al., 2015; Ma and Iturralde, 2016; Pan et al., 2016).

Therefore, the Hephaestus cable-driven robot was primarily developed for the CWM installation task, although various functions can be achieved by reprogramming the robot and replacing the end-effector. It is arguably the first cable-driven parallel robot (CDPR) in the world that is designed, built, and deployed specifically for curtain wall installation.

The CWM installation, as explained above, consists of four main steps: bracket installation, panel lifting, position adjusting, and panel fixation, which are the main tasks of the Hephaestus robot. The advantages of the robot are the large range of workspace, high payloads, reconfigurability, and modularity, making the system easily transportable and highly adjustable to adapt to various situations.

In terms of geometry, a CDPR is a configuration of cables with variable lengths connecting a drawing point attached to the base frame, and a fixing point attached to the mobile platform. The geometrical design of the CDPR can be defined by the following parameters: (1) number of cables, (2) geometry of the structure, (3) geometry of the platform, and (4) cable configurations. Previous studies indicate that CDPR driven by eight cables will have appropriate performance, thus the number of cables was chosen (Gouttefarde et al., 2015). The geometries of the structure and platform were determined by the positions of the drawing points and attachment points, respectively.

The Hephaestus CDPR consists of seven subassemblies. There are two drawing point assemblies on the top of the building, and four on the bottom, controlling the lengths of the cables (see Figure 4-5 a). In the center is the working platform subassembly, featuring eight fixing points, as well as the power system and various tools for the modular end-effector. In the Hephaestus project, two major tasks need to be performed: (1) the fixation of the bracket onto the concrete slab, which is performed by the robotic arm (see Figure 4-6), and (2) the placement of the CWMs onto the brackets by a vacuum system attached to the bottom of the CDPR platform (see Figure 4-5 b). In addition, a linear system with vacuum cups serving as a stabilizer is also integrated in the platform in order to stabilize the working platform subassembly (see Figure 4-7) (Iturralde et al., 2020).



(a) (b)

Figure 4-5: (a) Design of the Hephaestus cable-driven parallel robot (CDPR) prototype; (b) detailed depiction of the modular end-effector of the CDPR system

In addition, the CDPR features a control room (i.e., a small movable container equipped with computers and other relevant devices) which serves as the “brain” of the system. Currently, the CDPR (prototype) does not directly integrate advanced digital construction technologies. The main tasks, such as bracket installation and CWM positioning, are preprogrammed based on traditional CAD drawings. However, since the CDPR is equipped with adequate hardware and software capabilities, it certainly has the potential to integrate digital construction technologies, such as building information modeling (BIM) and digital twin, in future iterations in order to enhance its speed and performance.

Figure 4-6: Robotic arm and its tools for bracket installation protected by weatherproof covers (photo: José David Jiménez-Vicaría).

Figure 4-7: Stabilizer attaching the robot platform to the concrete slab (photo: José David Jiménez-Vicaría)

4.3.4 Determining the scenario for evaluation

Based on discussions and communications with partners of the Hephaestus project, a presumptive scenario for comparison can be proposed, as below (see Table 4-2). In this scenario, it is assumed that the facade installation company (i.e., Focchi Group UK) owns the robot during its lifecycle, because the company generated 133.90 million US dollars in revenue in 2019, which is large enough to fully employ more than one Hephaestus robot system.

In the case of curtain wall installation, the service charge is highly case-dependent (i.e., not only decided by the working area, but also by the form and shape of facade, type of CWM, etc.) and thus not easy to determine broadly. Usually, the representatives at the construction company carefully evaluate the building and requirements and provide an offer to the client thereafter. Therefore, a situation is assumed where the two scenarios execute exactly the same amount of workload (thus yielding the same revenue) based on the productivity of one robot system. In this way, many uncertainties can be avoided in determining the revenue that the company can make in the two scenarios. Similar to the concept of a controlled experiment in biology, in this research the variable “revenue” is controlled. Then, the costs of adopting the robot system and the benefits of saving money by avoiding the conventional method are compared. In other words, the costs here equal the money spent to operate the robot system, and the benefits equal the money saved by not using the conventional CWM installation method.

Table 4-2: Conventional and alternative scenarios defined for the comparison

Category	Scenario 1	Scenario 2
Name	Hephaestus cable-driven robot	Conventional facade installation
Key beneficiary	Facade installation company (Focchi Group UK)	
Business model	Owning the robot	Paid based on working area, etc.
Primary location for calculation	United Kingdom	
Investment period	5 years (the assumed lifecycle of the robot according to the engineering partners in the project)	
Main equipment required	1 cable-driven robot	1 crane for positioning
Estimated average area per job	540 m2 (L30 m × H18 m; 1.5 m × 3 m per panel)	

4.3.5 Gathering data and proposing assumptions for calculating the costs of the conventional and alternative scenarios

The data needed for the calculation in the cash flow analysis table are collected by various means such as market research, online meetings, calls, and emails with key stakeholders (e.g., the facade installation partner, the robot developing partner). Based on the data-gathering activities, the following information, which is crucial to the calculation, is demonstrated in Table 4-3.

Table 4-3: Data collected for the cash flow analysis of the two scenarios

Category	Scenario 1	Scenario 2
Name	Hephaestus cable-driven robot	Conventional facade installation
Number of workers	3 workers for system setup and disassembly; 1 worker for robot operation	1 for crane operation; 5 for curtain wall module handling
Speed/performance	• ~15 min for one bracket installation • ~15 min for one CWM installation	~30 min/m^2
Total time needed per job	123 h in total: • 55 h setup • 60 h curtain wall installation • 8 h disassembly	270 h
Productivity weight coefficient	1	2.20
Jobs finished per year	14	6.36
Downtime per year (e.g., holidays, operational, extreme weather, etc.)	8 weeks	
Median wage of construction worker in the UK	15.47 € (14.05 GBP) per hour	
Annual wage increase	3% (commonly applied in the construction sector)	
Discount rate	0.1% (in the UK as of October 2020)	
Annual equipment maintenance costs	10%	

Note: In addition, detailed explanations of Table 2 are listed as follows

(1) The main financial beneficiary is a curtain wall installation company operating in the UK, because the main market of facade installation for the key beneficiary is in the UK.

(2) For the simplification of calculation, the table uses the median hourly rate of construction workers to calculate all the inputs related to labor costs.

(3) The estimated cost of the robot system includes manufacturing cost, logistics, administrative cost, and profit.

(4) The robot system does not cause extra administrative costs, compared to the conventional method.

(5) A one-month training cost of 12,000 € (3000 €/person) is added, to train four workers for operating the robot system during the downtime of the first year. During the training month, these workers' salary needs to be covered by the company as well (9900 €). After the training, one worker will become a highly skilled operator, thus earning 30% more salary than the average worker.

(6) The annual total saving outputs equal the annual saving inputs multiplied by a productivity weight coefficient of 2.2, which means that the alternative robot system is 2.2 times as productive as the conventional method. Therefore, the productivity weight coefficient needs to be considered in the conventional method to keep up with the productivity of the alternative robot system in order to achieve the same gross revenue for fair comparison.

(7) Regarding the central cost for the company, this robot system does not require additional special managerial efforts, compared to the conventional scenario. Therefore, central costs are not calculated in both scenarios.

4.3.6 Results

Based on the proposed comparison scenario and collected data in the case study, the following results can be presented, including cash flow analysis, key financial indicators, sensitivity analysis, and recommendations. According to the comparison of the conventional method and cable-driven robot method for facade installation, the cash flow analysis table can be filled in detail with corresponding numbers, as below (see Table 4-4).

Table 4-4: Cash flow analysis of the proposed robot system based on the UK market

Cashflow analysis to compare novel STCR solution and conventional method							
Key stakeholder/beneficiary	Curtain wall installing company						Operating region: UK
Cash outflows	Year 1	Year 2	Year 3	Year 4	Year 5	Total (€)	Explanation and remarks
Central - hardware costs						0.00	
Central - software costs						0.00	
Central - network costs						0.00	
Central - utility costs						0.00	
Central - operation						0.00	
Central - maintenance						0.00	
Central - other						0.00	
Per robot costs - hardware	600,000.00					600,000.00	
Per robot costs - software						0.00	
Per robot costs - network & utility	3,000.00	3,000.00	3,000.00	3,000.00	3,000.00	15,000.00	
Per robot costs - training	21,900.00					21,900.00	
Per robot costs - transport	5,000.00	5,000.00	5,000.00	5,000.00	5,000.00	25,000.00	
Per robot costs - installation	35,735.70	36,807.77	37,912.00	39,049.36	40,220.85	189,725.68	
Per robot costs - operation	16,893.24	17,400.04	17,922.04	18,459.70	19,013.49	89,688.51	
Per robot costs - disassembly	5,197.92	5,353.86	5,514.47	5,679.91	5,850.30	27,596.46	
Per robot - maintenance	60,000.00	60,000.00	60,000.00	60,000.00	60,000.00	300,000.00	
Per robot - other						0.00	
Total outflow	747,726.86	127,561.67	129,348.52	131,188.97	133,084.64	1,268,910.65	
Savings - equipment	50,000.00	50,000.00	50,000.00	50,000.00	50,000.00	250,000.00	
Savings - labor	159,390.50	164,172.22	169,097.39	174,170.31	179,395.42	846,225.83	
Savings - utility	1,000.00	1,000.00	1,000.00	1,000.00	1,000.00	5,000.00	
Savings - operational						0.00	
Savings - maintenance	5,000.00	5,000.00	5,000.00	5,000.00	5,000.00	25,000.00	
Savings - other						0.00	
Total savings	473,859.11	484,378.88	495,214.25	506,374.68	517,869.92	2,477,696.83	
Net annual cashflow	-273,867.75	356,817.22	365,865.73	375,185.70	384,785.28	1,208,786.18	
Net cumulative cashflow	-273,867.75	82,949.47	448,815.20	824,000.90	1,208,786.18	1,208,786.18	
Coefficient of productivity	2.20						
Annual wage increase	1.03						

4.3.6.1 Key financial indicators of the Hephaestus cable robot

As mentioned above, the key financial indicators relevant in this evaluation can be calculated based on the results of the cash flow analysis (Figure 9), including benefit–cost ratio (BCR), return on investment (ROI), payback period (PBP), initial investment value (IIV), and net present value (NPV) (Boardman et al., 2018). The key financial indicators are calculated based on the following equations:

(1) BCR = (|present value of benefits|)/(|present value of costs|)

(2) ROI = (total cost savings – total outflows)/(|total outflows|)

(3) PBP = n + (|net accumulative cash flow of year n|)/(net annual cash flow of year n + 1),

n represents the number of the final year with negative net accumulative cash flow.

(4) IIV = (initial hardware cost) + (initial deployment cost)

(5) NPV = (net annual cash flow)/(1 + cost of money)$^{\text{Years in the future}}$

As a result, the key financial indicators of the Hephaestus cable-driven robot for curtain wall installation are calculated, as below (see Table 4-4).

Table 4-5: Key financial indicators of the proposed robot system when operating in the UK

Key Financial Indicator	Value

Benefit–Cost Ratio (BCR)	1.95
Return on Investment (ROI)	95.26%
Payback Period (PBP)	21.21 months
Initial Investment Value (IIV)	747,726.86 €
Net Present Value (NPV)	1,205,040.19 €

Note: The definitions of the key financial indicators are listed as follows:

(1) BCR indicates the overall relationship between the relative benefits and costs of a proposed project. In this case study, benefits refer to the money saved by not using the conventional facade installation method, and costs refer to the money spent to operate the robot system. If the value is larger than 1.0, the project is expected to deliver economic satisfaction to its investors.

(2) ROI is a performance measure used to evaluate the efficiency of an investment.

(3) PBP is the period of time required to recover the cost of an investment.

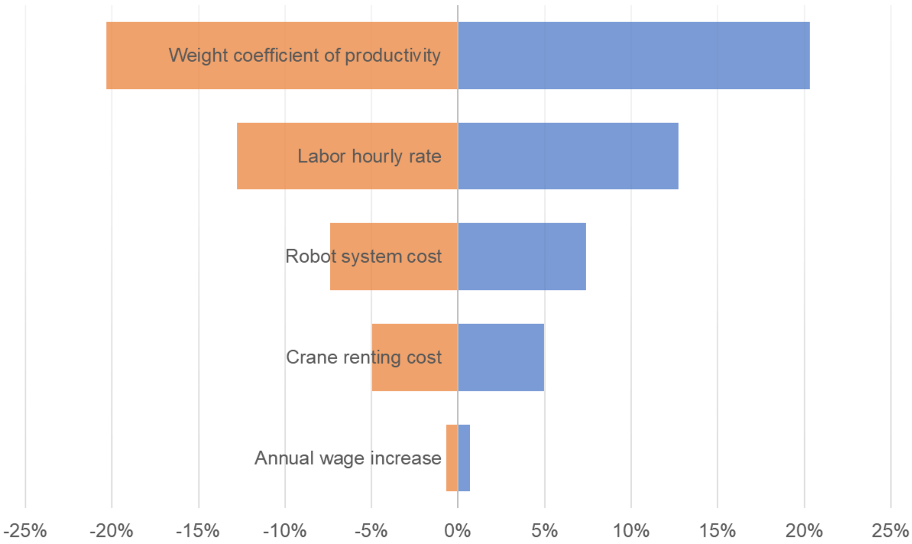
(4) IIV is defined here as the amount of money needed for the total capital expenditures in the first year.

(5) NPV is the current value of a future stream payments. Here it refers to the present value of the total net accumulative cash flow.

4.3.6.2 Sensitivity analysis

Sensitivity analysis, also known as what-if analysis, is a financial tool which determines how target outputs are affected based on changes in input variables. This model is used to predict the result of a decision, given a certain set of variables. There are a wide range of uses of sensitivity analysis, which can be categorized into four main aspects: decision-making support, communication, increasing understanding of the system, and model development (Pannell, 1997). Based on this tool, the analyst will be able to understand which input variable is more consequential, and which one is less.

Therefore, a simple sensitivity analysis is conducted, regarding several major variables in the cash flow analysis. By adjusting each input variable 10% better and 10% worse, the total accumulative cash flow by the end of the five-year period will also change accordingly. Thus, the increase and decrease of total accumulative cash flow, compared to the original estimation, can be calculated. In this case, five main input variables, including annual wage increase, labor cost (hourly rate), robot system cost, crane renting cost, and productivity coefficient weight, are evaluated. The result is shown in Table 4-8.



	Annual wage increase	Crane renting cost	Robot system cost	Labor hourly rate	Weight coefficient of productivity
Positive	1%	5%	7%	13%	20%
Negative	-1%	-5%	-7%	-13%	-20%

Figure 4-8: Sensitivity analysis of the CBA

From the sensitivity analysis, it can be concluded that the outcome is most sensitive to the weight coefficient of productivity, followed by labor hourly rate, robot system cost, crane renting cost, and last, but not least, the annual wage increase. Other variables, such as utility cost and training cost, are not listed here due to their relative insignificance to the outcome of the analysis. The sensitivity analysis is especially important and insightful because many data acquired in this study are only rough estimations. It indicates that the most efficient way to improve profitability or benefits of the alternative system is to further improve the productivity and efficiency of the robot, although this objective might be difficult to achieve.

4.3.6.3 Recommendations

As mentioned in the beginning of this chapter, the last part of CBA, usually, is to make a recommendation on whether the alternative option is worth considering. The results of key financial indicators indicate that the BCR is 1.95, which exceeds 1. Therefore, the investment of the Hephaestus cable-driven robot for CWM installation, based on the UK market, is projected to be economically acceptable and efficient. In particular, the investment of one Hephaestus cable-driven robot system could pay for itself in only 21.21 months (i.e., within two years) when operated in the UK.

In accounting, the break-even point (BEP) refers to the time point at which the total cost and total revenue are equal (Dayananda et al., 2002). When adjusting the net cumulative cash flow to near zero in year 5, by adjusting the construction worker salary while keeping any other variables the same, it can be inferred that the investment of the Hephaestus cable-driven robot system will be worthwhile, in theory, if the local hourly wage for workers is higher than approximately 3.45 €/h. In other words, the proposed robot system for curtain wall installation task will be financially competitive in countries or regions where the median salary for a construction worker is above 3.45 €/h as of 2020, which is the BEP.

Furthermore, Table 4-6 demonstrates whether the Hephaestus cable-driven robot system is competitive in the G20 countries/regions (different currencies are converted to euros based on the exchange rates on 13th October 2020, according to Google). In this research, if the local median wage of construction workers is more than double the BEP, the investment will be defined as highly competitive; if the local median wage of construction workers is more than the BEP but less than double the BEP, it will be defined as competitive; otherwise, it will be considered as uncompetitive. Therefore, the table shows that the proposed system would currently be highly competitive, compared to the conventional method in most developed countries in the world, and it would be relatively competitive in many emerging economies as well, with a few exceptions such as Argentina, Brazil, China (mainland), India, Mexico, Russia, South Africa, and Turkey (according to www.salaryexpert.com and www.salaryexplorer.com as of October, 2020). However, as the economy continues to expand in these emerging markets and their average income of workers increases, it is predictable that the proposed system will become competitive in these countries as well in the near future.

Table 4-6: Median hourly rate of construction workers in G20 countries/regions, and indications on whether the robot is competitive in the respective country (source: www.salaryexpert.com and www.salaryexplorer.com)

G20 Country or Region	Median Hourly Rate (in €)	Recommendation
Argentina	2.19 (198.68 ARS)	Uncompetitive
Australia	18.23 (29.93 AUD)	Highly competitive
Brazil	3.18 (21.07 BRL)	Uncompetitive
Canada	14.93 (23.23 CAD)	Highly competitive
China (mainland)	3.41 (27.25 CNY)	Uncompetitive
China (Hong Kong)	13.01 (118.60 HKD)	Highly competitive
France	14.15	Highly competitive
Germany	17.18	Highly competitive
India	1.15 (99.17 INR)	Uncompetitive
Indonesia	3.59 (62053.86 IDR)	Competitive
Italy	13.08	Highly competitive
Japan	14.66 (1826.55 JPY)	Highly competitive
Mexico	2.41 (60.66 MXN)	Uncompetitive
Russia	2.11 (192.16 RUB)	Uncompetitive
Saudi Arabia	8.69 (38.24 SAR)	Highly competitive
South Africa	3.12 (60.99 ZAR)	Uncompetitive

South Korea	10.18 (13,790.48 KRW)	Highly competitive
Turkey	2.51 (23,41 TRY)	Uncompetitive
United Kingdom	15.47 (14.05 GBP)	Highly competitive
United States	17.28 (20.29 USD)	Highly competitive

Likewise, the competitiveness of the façade installation cable driven robot in EU-28 states also can be estimated below (see Table 4-7). The statistics show that in almost all EU-28 states except Bulgaria, the proposed façade installation cable robot is highly competitive or competitive, indicating also a large potential in Europe.

Table 4-7: Median hourly rate of construction workers in EU-28 states, and indications on whether the robot is competitive in the respective country (source: www.salaryexpert.com and www.salaryexplorer.com)

EU-28 states	Median Hourly Rate (in €)	Recommendation
Austria	19.60	Highly competitive
Belgium	19.18	Highly competitive
Bulgaria	2.97 (5.82 BGN)	Uncompetitive
Croatia	4.18 (31.62 HRK)	Competitive
Cyprus	7.62	Highly competitive
Czech Republic	6.97 (18870 CZK)	Highly competitive
Denmark	26.27 (195.49 DKK)	Highly competitive
Estonia	6.55	Competitive
Finland	20.94	Highly competitive
France	14.15	Highly competitive
Germany	17.18	Highly competitive
Greece	9.24	Highly competitive
Hungary	4.09 (1457.69 HUF)	Competitive
Ireland	20.07	Highly competitive
Italy	13.08	Highly competitive
Latvia	6.07	Competitive
Lithuania	7.79	Highly competitive
Luxembourg	20.82	Highly competitive
Malta	8.27	Highly competitive
Netherlands	20.28	Highly competitive
Poland	5.98 (26.71 PLN)	Competitive

Portugal	8.24	Highly competitive
Romania	3.85 (18.75 RON)	Competitive
Slovakia	7.00	Highly competitive
Slovenia	7.21	Highly competitive
Spain	10.56	Highly competitive
Sweden	17.72	Highly competitive

The results are important indicators for companies and policy makers in different countries and regions to decide whether the investment of the Hephaestus cable-driven robot is worth considering. Furthermore, as the manufacturing costs of the robot system drop and the global labor costs increase over time, it is foreseeable that the robot system will be competitive in even more countries worldwide.

4.3.7 Discussion

This research introduces a simple framework for economically evaluating single-task construction robots, based on a case study of a cable-driven curtain wall installation robot. The results indicate that the CDPR system in the case study is financially competitive in the UK, as well as in most developed countries or regions. The advantages and future validation of the methods, as well as the additional socioenvironmental implications, limitations, adaptability, and reproducibility, are further discussed in the sections below.

4.3.7.1 Advantages and future validation of the methods

This case study mainly discussed the direct economic implications of STCR, using the proposed cable-driven robot for curtain wall installation as a case study. It will be one of the first CBA research instances focusing on STCRs, setting a valuable precedent for the field of construction robots.

The methodology is practical and helpful for the key beneficiary (e.g., the construction company) to make decisions about whether to invest in construction robots without acquiring large amounts of data. The calculation method is specifically designed to estimate the costs and benefits of an advanced solution for a specific task in a short amount of time. Therefore, it does not require a large amount of time and effort of the key beneficiary, such as historical data collection and opinion survey.

Further, the proposed framework, as well as the results, can be further validated by the key beneficiary through a real-world pilot project in which the key performance indicators (KPIs) of the conventional and alternative scenarios (e.g., speed, performance, cost, etc.) can be more accurately measured.

4.3.7.2 Further socio-environmental implications

The proposed methods mainly address the direct microeconomic evaluation of an STCR, compared to the traditional technique, through a simplified analyzing framework. However, more indirect socio-environmental implications, other than productivity increase, are also worth noting. For instance, the STCR approach enhances labor safety. According to Eurostat, there were 3552 fatal accidents at work in EU-28 states during 2017, of which one fifth happened in the construction sector (Eurostat, 2020). In other words, more than 700 accidental deaths took place within the construction industry in EU countries just in 2017. The reduction in the number of onsite construction workers at height, through applying construction robots, can substantially reduce the chance of fatal accidents and other injuries on the construction sites. Furthermore, the application of STCRs has a positive impact on construction quality through precise control and real-time monitoring, which potentially benefits the reputation and profitability of the relevant construction companies. Meanwhile, it also has a positive impact on resource consumption due to the precise automatic control system (Bock and Linner, 2016a). Moreover, the vacancy rate in the construction sector (excluding the real estate subsector) in the EU28 increased by 1.7% from 2010 to 2018, indicating growing labor shortages in the business. In particular, Germany observed 121,736 unfilled positions in the construction sector in 2018, compared to only 51,892 in 2010 (European Commission, 2020). The implementation of robots can help alleviate the growing labor shortages in the construction business. These aspects obviously make an even stronger case in favor of construction robots, although these additional socio-environmental benefits are more difficult to monetize.

4.3.7.3 Limitations

Just like any other economic models, this initial CBA is by no means an impeccable process. The results reported in this section have certain limitations, summarized as follows.

(1) The usability of the alternative scenario, currently based on a prototype, needs to be further tested and validated in real-world practice.

(2) Many data for calculation are only rough estimations, and more accurate data might be possible in the future.

(3) The manufacturing cost of the robot is only calculated based on prototyping cost in the EU market, thus cheaper alternatives, such as outsourcing, are not considered, and future mass production might be substantially lower.

(4) Many long-term indirect socio-environmental benefits are difficult to quantify and monetize. Also, the primary beneficiary in the case study is defined as the facade installation company. Therefore, the indirect socio-environmental benefits are not included directly in the case study.

4.3.7.4 Adaptability and reproducibility

As shown in previous sections, the case study provides a simple, but useful, tool to assess the benefit and cost of any given STCR system, which fills the gap in the economic evaluation of construction robots. The demonstrated process of CBA for STCR is highly adaptable and reproducible. Therefore, researchers, engineers, investors, and policy makers can easily follow and customize this method to assess the economic advantages of any STCR system and similar systems, compared to traditional techniques and methods. Case Study II presented in the following sections is an example of applying this framework to analyzing other robotic and automated systems in the healthcare industry.

4.4 Case Study II: Smart furniture solution based on PI^{2}Us

Older adults in Europe currently compose an expanding proportion of the population year after year. Meanwhile, many chronic diseases tend to mainly affect the elderly community. As a result, the European health expenditure is expected to significantly increase. To make matters worse, there is an ongoing labor shortage in the European healthcare system. For instance, in Germany alone, a shortage of 840,000 health and social workers in Germany by 2030 is predicted (Prognos A.G., 2011). The ongoing COVID-19 pandemic only worsens the situation. Research reported that increasing the level of activity is beneficial to older adults' health status and thus can potentially contain the health expenditure growth (McPhee et al., 2016). In the REACH project, one of the key concepts is the PI^{2}U, which is a special type of smart furniture that seamlessly integrates the functionality of REACH in order to promote the level of activity and independence of older adults. However, whether the economic efficiency of the PI^{2}Us can excel that of the traditional care techniques remains unclear. Therefore, an evaluation of the economic performance of smart furniture systems is needed to answer this question.

In Case Study I, it was proved that the façade installation cable robot (i.e., a construction robot) was worth investing in the majority of G20 countries as well as in nearly all EU-28 states (the only exception was Bulgaria). As a result, the proposed framework was verified to be useful and effective in evaluating the economic performance of a construction robot. Due to the similarities between STCRs and Ambient Rehabilitation Kits such as they both use automation and sensing technology to offset human labor shortages and are both developed based on modular principles and platform strategy, it is appropriate and reasonable to apply this framework to conducting a CBA of the Ambient Rehabilitation Kit based on the PI^{2}Us (Hu et al., 2019).

4.4.1 Methods

As discussed above, CBA is deemed to be one of the most important problem-solving tools in the decision-making process, yet there is a lack of research on the CBA of smart home solutions for aging society. One of the few examples is the framework proposed by Nagar et al. which was designed to evaluate the costs and benefits of the devices in smart home systems, but it focused on the benefits of reducing energy consumption and lost thanks to the implementation of smart sensing and metering hardware (Nagar et al., 2016). In the emerging field of smart furniture-based smart home solutions, such research emphasizing the benefits and costs of substitute human care givers with smart furniture is also needed.

Therefore, based on the methods proposed in this chapter, the following section focuses on using the simple framework to evaluate economically smart furniture solutions compared to traditional care methods in various care environments. The data inputs for this CBA were acquired via market search and interviews with professional care providers. According to the results of the CBA, it can be concluded that the smart furniture solutions developed in this project are worth investing by hospitals and the overall healthcare system in Germany, potentially soothing the labor shortage in the healthcare system. Furthermore, the significance and limitations of this CBA are also discussed below. The goals of this research mainly include the following aspects: 1) to explore whether the smart furniture solutions developed in REACH Touchpoint 2 are worth investing by hospitals and overall healthcare system in Germany, 2) to provide evidence for the policy makers to decide how much resources shall be allocated to the relevant technologies, and 3) to establish a methodological example of conducting CBA for smart furniture solutions in the context of aging society.

4.4.2 Analytical framework

The CBA followed the same analytical framework proposed in Section 4.2 (see Figure 4-1). Due to the public welfare nature of the Ambient Rehabilitation Kit, it is appropriate to extend the calculation period from five years to seven years. The items of the cash flow analysis table were adjusted accordingly based on the features of the Ambient Rehabilitation Kit (see Table 4-8).

Table 4-8: Cash flow analysis table for the Ambient Rehabilitation Kit compared to conventional caregiving method

AAL Service Financial Evaluation									
Cash outflows	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Total (€)	Remarks
Central - hardware costs								0	
Central - software costs								0	
Central – network costs								0	
Service implementation								0	
Per patient costs - hardware								0	
Per patient costs - software								0	
Per patient costs - network								0	
Per patient costs - install								0	
Per patient costs - support								0	
Per patient costs - discharge								0	
Other - maintenance								0	
Total outflow	0	0	0	0	0	0	0	0	
Savings - in-patient								0	
Savings - emergency dep.								0	
Savings - home visits								0	
Savings - primary care								0	
Savings - long term care								0	
Other								0	
Cost savings	0	0	0	0	0	0	0	0	
Net annual cashflow	0	0	0	0	0	0	0	0	
Net cumulative cashflow	0	0	0	0	0	0	0	0	

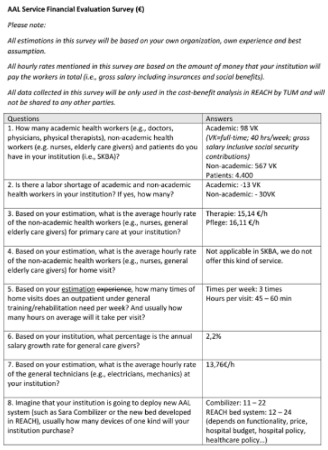
4.4.3 Determining scenarios for comparison

In order to define and analyze the scenarios for the comparison, a workshop was organized among the key partners in the REACH project, including medical device manufacturers, professional caregivers, and business consultants. As a result, in the "To Market" Workshop at Technical University of Munich on October 7th and 8th, 2019, the participated partners co-created three suitable comparison scenarios for the PI^{2}U solutions in REACH (see Table 4-9).

Table 4-9: Three proposed comparison scenarios for the PI²U solutions in REACH

Categories	**Scenario 1**	**Scenario 2**	**Scenario 3**
Name	Community prevention	Rehabilitation hospital + follow-up + readmission	Care home (quality of life)
For whom	Communities (e.g., townships, municipalities, etc.)	Decision makers (CEOs, heads of hospitals), caregivers	Caregivers, decision makers (heads of care homes)
Medical claim	• Healthy aging (fall-prevention, social/physical activity, ADLs, etc.)	• Lower hospital cost • Shortened hospital stays • Better patient experience	• Higher satisfaction • Higher quality of life
Environment	• Independent life at home • Community / village	• Rehabilitation hospital + home	• Care home (20-100 users/units)
Time (application/ investment)	• 15-25 years (after retirement) • 5-7 years	• 3 weeks + 3 months • 5-7 years	• 2 years (average stay period at care home) • 5-7 years
Product level	Non-medical level	Medical level device	Non-medical level or non-risk class
Proposed solution	MiniArc + iStander	SilverBed + ActivLife	iStander + ActivLife

The cash flow analysis was completed to calculate the key financial indicators of each scenarios. The calculation was based on the cash flow analysis table (see Table 4-8). Furthermore, the data was collected via market search and questionnaires with partners (see Figure 4-9).



AAL Service Financial Evaluation Survey (€)

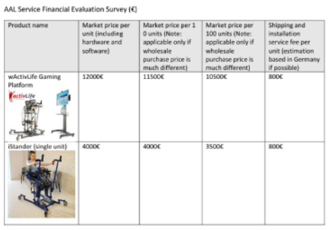
Please note:

All estimations in this survey will be based on your own organization, own experience and best assumption.

All hourly rates mentioned in this survey are based on the amount of money that your institution will pay the workers in total (i.e., gross salary including insurances and social benefits).

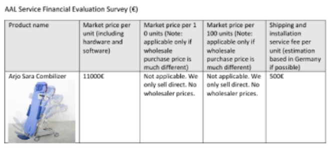
All data collected in this survey will be only used in the cost-benefit analysis in REACH by TUM and will not be shared to any other parties.

Questions	Answers
1. How many academic health workers (e.g., doctors, physicians, physical therapists), non-academic health workers (e.g. nurses, elderly care givers) and patients do you have in your institution (i.e., SKBA)?	Academic: 98 VK *(VK=full-time; 40 hrs/week; gross salary inclusive social security contributions)* Non-academic: 567 VK Patients: 4.400
2. Is there a labor shortage of academic and non-academic health workers in your institution? If yes, how many?	Academic: -13 VK Non-academic: - 30VK
3. Based on your estimation, what is the average hourly rate of the non-academic health workers (e.g., nurses, general elderly care givers) for primary care at your institution?	Therapie: 15,14 €/h Pflege: 16,11 €/h
4. Based on your estimation, what is the average hourly rate of the non-academic health workers (e.g., nurses, general elderly care givers) for home visit?	Not applicable in SKBA, we do not offer this kind of service.
5. Based on your estimation ~~experience~~, how many times of home visits does an outpatient under general training/rehabilitation need per week? And usually how many hours on average will it take per visit?	Times per week: 3 times Hours per visit: 45 – 60 min
6. Based on your institution, what percentage is the annual salary growth rate for general care givers?	2,2%
7. Based on your estimation, what is the average hourly rate of the general technicians (e.g., electricians, mechanics) at your institution?	13,76€/h
8. Imagine that your institution is going to deploy new AAL system (such as Sara Combilizer or the new bed developed in REACH), usually how many devices of one kind will your institution purchase?	Combilizer: 11 – 22 REACH bed system: 12 – 24 (depends on functionality, price, hospital budget, hospital policy, healthcare policy...)



AAL Service Financial Evaluation Survey (€)

Product name	Market price per unit (including hardware and software)	Market price per 1 0 units (Note: applicable only if wholesale purchase price is much different)	Market price per 100 units (Note: applicable only if wholesale purchase price is much different)	Shipping and installation service fee per unit (estimation based in Germany if possible)
wActivLife Gaming Platform	12000€	11500€	10500€	800€
iStander (single unit)	4000€	4000€	3500€	800€



AAL Service Financial Evaluation Survey (€)

Product name	Market price per unit (including hardware and software)	Market price per 1 0 units (Note: applicable only if wholesale purchase price is much different)	Market price per 100 units (Note: applicable only if wholesale purchase price is much different)	Shipping and installation service fee per unit (estimation based in Germany if possible)
Arjo Sara Combilizer	11000€	Not applicable. We only sell direct. No wholesaler prices.	Not applicable. We only sell direct. No wholesaler prices.	500€

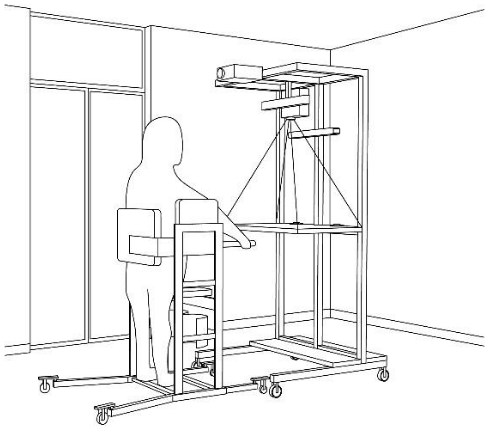
Figure 4-9: Examples of feedback questionnaires from partners

4.4.4 Results

Based on the proposed comparison scenarios and collected data in the case study, the following results can be presented, including cash flow analysis, key financial indicators, sensitivity analysis, and recommendations. The prerequisites and assumptions of each scenario are discussed in detail in the notes below the cash flow analysis tables.

4.4.4.1 Scenario 1: "MiniArc + iStander" vs traditional community/home aging

This scenario is to compare the "MiniArc + iStander" home/community healthy aging system to the traditional community/home aging (see Figure 4-10). The target users are healthy older individuals who want to be physically and cognitively active in the community during retirement. The main focus is prevention and healthy aging. It is appropriate to calculate up to seven years due to the nature of an Ambient-Assisted Living (AAL) system (e.g., high in initial investment, incrementally effective), although many evaluations only consider five years. Table 2-2 is the cash flow analysis of Scenario 1 over seven years.



vs.

Figure 4-10: Scenario 1: "MiniArc + iStander" vs traditional community/home aging (photo obtained from Microsoft 365 royalty-free stock image library)

Table 4-10: Cash flow analysis table of Scenario 1

Scenario 1									
Ambient Rehab System Financial Evaluation: MiniArc + iStander for healthy aging (vs. tradition home/community aging)									
Cash outflows	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Total (€)	Remarks
Central - hardware costs	12000							12000	4000+8000
Central - software costs								0	
Central - network costs	500	500	500	500	500	500	500	3500	
Service implementation	8880	7280	7280	7280	7280	7280	7280	52560	Install + utility bill + room rent + admin
Per patient costs - hardware								0	
Per patient costs - software								0	
Per patient costs - network								0	
Per patient costs - install								0	
Per patient costs - support								0	
Per patient costs - discharge								0	
Other - maintenance	400	400	400	480	480	480	480	3120	Training, maintenance & annual overhaul
Total outflow	21780	8180	8180	8260	8260	8260	8260	71180	
Savings - in-patient	600	600	600	600	600	600	600	4200	Membership fee: 50*12
Savings - emergency dep.								0	
Savings - home visits								0	
Savings - primary care								0	
Savings - long term care								0	
Other - value of a life year	14464	14464	14464	14464	14464	14464	14464	101248	86783€(~95640$)*3/18
Cost savings	15064	15064	15064	15064	15064	15064	15064	105448	
Net annual cashflow	-6716	6884	6884	6804	6804	6804	6804	34268	
Net cumulative cashflow	-6716	168	7052	13856	20660	27464	34268	34268	

Note: This cash flow analysis is calculated based on the following assumptions:

(1) The main financial and social beneficiary of Scenario 1 is the community, township, municipality, or society as a whole.

(2) The scenario of 15 years of retired life is based on the facts that the current average retirement age in Germany is 66 years old and the current life expectancy in Germany is about 81 years old.

(3) The current one-time cost of the hardware "MiniArc + iStander" or alternatively "activLife Platform" is €12,000 each.

(4) It is assumed that a township or municipality invests in the proposed solution

(MiniArc + iStander) to establish a local community training center. Every device needs to be administrated by 20% of one social worker's labor. The service implementation includes the one-time installation, utility bill, room rent, and the administrative cost per set of devices.

(5) In this scenario, the shadow price of some social benefits is more important because the main beneficiary is the township or municipality as a whole (i.e., the government or even society). For example, according to Abelson, the value of a life year should be $95,640 in US dollars (Abelson, 2003), which is lower than many other estimations (Zaloshnja et al., 2004). In addition, research suggested that a conservative estimate of the net increase in life expectancy for being physical active is about two to four years per person (Reimers et al., 2012). Therefore, it can be assumed that one set of devices if fully utilized in Scenario 1 (either "MiniArc + iStander" or "ActivLife Platform") can increase in general three life-years of the local residents, which can be equally distributed into each year of the extended total 18 years of retirement.

(6) Unlike STCRs which are heavy-duty requiring a high maintenance cost of 10% of the hardware, the PI^2Us are used indoors, leading to a lower maintenance cost. It is assumed that the maintenance costs of the system increase 20% after three years of usage.

(7) Unlike STCRs, all of the PI^2Us are user-friendly and plug-and-play. Therefore, the training costs are negligible.

According to the cash flow analysis, the key financial indicators of Scenario 1 can be calculated, see Table 4-11.

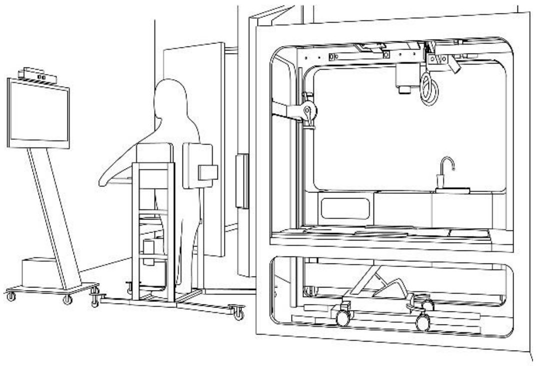
Table 4-11: Key financial indicators of Scenario 1

Key financial indicator	Value
Benefit–Cost Ratio (BCR)	1.48
Return on Investment (ROI)	48.14% (over 7 years)
Payback Period (PBP)	2 years or 24 months
Initial Investment Value (IIV)	€13,600
Net Present Value (NPV)	Applicable when interest rate is positive

Note: As social values of the proposed solution for society were considered (see Table 3 3), the ROI per invested set of devices in Scenario 1 is 48.14% over 7 years. The PBP is two years or 24 months. IIV is €13,600 per invested set of devices. The NPV is not calculated here because the current German Central Bank discount rate is below zero (-0.88%), and the seven-year German government bond is below zero as well (-0.745%). Of course, in countries where the discount rate is currently positive (e.g., China, etc.), it is necessary to calculate the NPV for each investment.

4.4.4.2 Scenario 2: "SilverBed + ActivLife" vs traditional hospital rehabilitation

This scenario is to compare the "SilverBed + ActivLife" rehabilitation and living support system to the traditional hospital rehabilitation (see Figure 4-11). Table 2-2 is the cash flow analysis of Scenario 1 over seven years. The table is highly flexible and comprehensive and can be adapted to many different scenarios. The target users are older patients who stay in hospital and need physical therapists and primary caregivers to rehabilitate. The main focus is rehabilitation. The patient uses a SilverBed system and an ActivLife system in his/her room to live as independent as possible.



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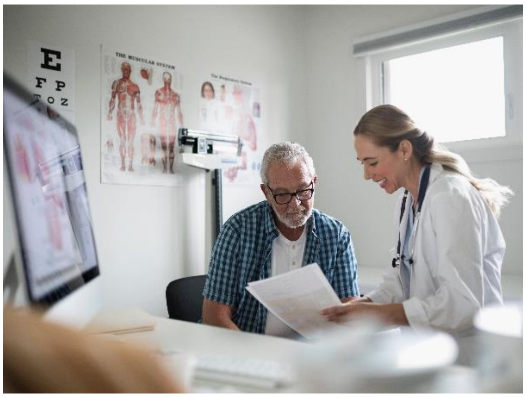


Figure 4-11: Scenario 2: "SilverBed + ActivLife" vs traditional hospital rehabilitation (photo obtained from Microsoft 365 royalty-free stock image library)

Table 4-12: Cash flow analysis table of Scenario 2

Scenario 2									
Ambient Rehab System Financial Evaluation: PI^{2}U-SilverBed and ActivLife Platform (vs. traditional rehabilitation at hospital)									
Cash outflows	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Total (€)	Remarks
Central - hardware costs								0	
Central - software costs								0	
Central – network costs								0	
Service implementation	200	200	200	200	200	200	200	1400	Maximum utility bill for the system
Per patient costs - hardware	36750							36750	20000+11000+11500/2
Per patient costs - software								0	
Per patient costs - network	250	250	250	250	250	250	250	1750	500/2
Per patient costs - install	1600							1600	1200+800/2
Per patient costs - support	3250	3322	3395	3469	3546	3624	3703	24309	1*15.14*2*52+1*16.11*2*52=1575+1675
Per patient costs - discharge								0	
Other - maintenance	800	800	800	960	960	960	960	6240	Training, maintenance & annual overhaul
Total outflow	42850	4572	4645	4879	4956	5034	5113	72049	
Savings - in-patient	2750	2750	2750	2750	2750	2750	2750	19250	55*50 (55=0.15*365)
Savings - emergency dep.								0	
Savings - home visits								0	
Savings - primary care	9750	9965	10184	10408	10637	10871	11110	72925	1*15.14*6*52+1*16.11*6*52=4724+5026
Savings - long term care								0	
Other								0	
Cost savings	12500	12715	12934	13158	13387	13621	13860	92175	
Net annual cashflow	-30350	8143	8289	8279	8431	8587	8747	20126	
Net cumulative cashflow	-30350	-22207	-13918	-5639	2792	11379	20126	20126	

Note: This cash flow analysis is calculated based on the following assumptions:

(1) The main financial beneficiary of Scenario 2 is the owner of the hospital.
(2) The current one-time cost of the hardware "SilverBed + ActivLife" is €36,750 (i.e., one patient uses a SilverBed and share a ActivLife with another patient), but because it is calculated based on the cost of prototypes, as time goes by and the products enter mass production process, the hardware cost will likely reduce over time.
(3) In traditional rehabilitation scenario, it is assumed that without the proposed system, one physical therapist needs to work for six hours per week and another primary caregiver needs to work for six hours per week for the rehabilitation of one patient. In the proposed scenario, one physical therapist and one primary caregiver only need to work for two hours each per week to assist the rehabilitation of the patient.
(4) A 2.2% annual salary increase is considered.
(5) It is assumed that by applying the "SilverBed + ActivLife" system, 15% of the in-patient time can be reduced, and one reduced in-patient day can save the hospital €50 on average for accepting new patients.
(6) According to the hospital partner Schön Klinik, the hourly cost of a physical therapist is €15.14 and of a primary caregiver is €16.11 for the hospital.

According to the cash flow analysis, the key financial indicators of Scenario 2 can be calculated, see Table 4-13.

Table 4-13: Key financial indicators of Scenario 2

Key financial indicator	Value
Benefit–Cost Ratio (BCR)	1.28
Return on Investment (ROI)	27.93% (over 7 years)
Payback Period (PBP)	4.7 years or 56 months
Initial Investment Value (IIV)	€38,350
Net Present Value (NPV)	Applicable when interest rate is positive

As indicated in Table 4-13, the ROI of Scenario 2 is 27.93% over seven years per set of devices (i.e., one SilverBed and half an activLife Platform). The PBP is 4.7 years or 56 months. The IIV is €38,350 per set of devices. The NPV is also not considered due to the reason mentioned above (i.e., negative discount rate in Germany).

4.4.4.3 Scenario 3: "iStander + ActivLife" vs traditional care home

This scenario is to compare the "iStander + activLife" home rehabilitation system to the traditional care home (see Figure 4-12). The target users are older adults living in care homes who want to improve their physical and cognitive condition, thus achieving higher quality of life. The main focus is to improve the quality of life as well as to increase the productivity of caregivers. Table 4-14 is the cash flow analysis of Scenario 3 over seven years.

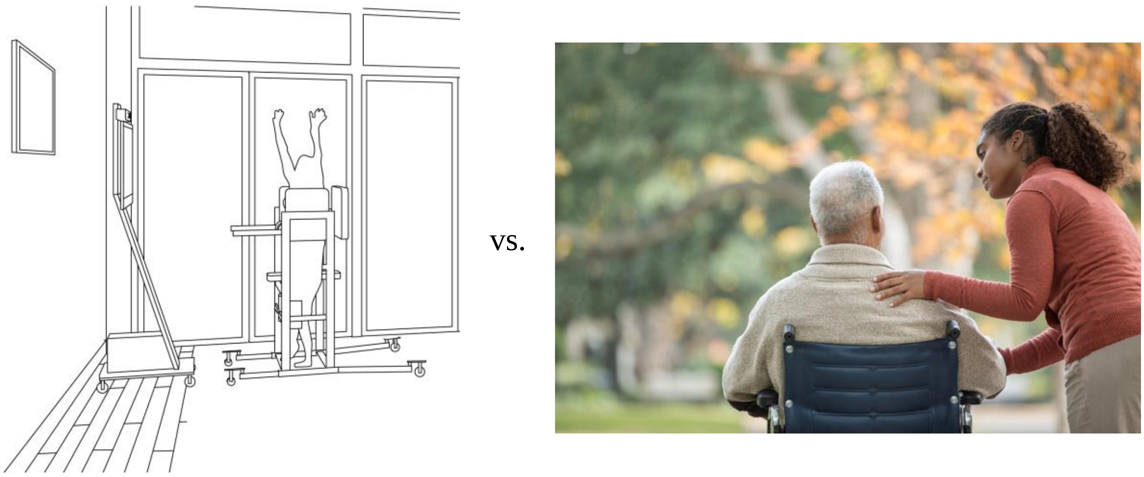


Figure 4-12: Scenario 3: "ActivLife + iStander" vs traditional care home (photo obtained from Microsoft 365 royalty-free stock image library)

Table 4-14: Cash flow analysis table of Scenario 3

Scenario 3									
Ambient Rehab System: iStander and ActivLife Platform (vs. traditional care home)									
Cash outflows	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Total (€)	Remarks
Central - hardware costs								0	
Central - software costs								0	
Central – network costs								0	
Service implementation	200	200	200	200	200	200	200	1400	Maximum utility bill for the system
Per patient costs - hardware	5500							5500	4000+12000/8
Per patient costs - software								0	
Per patient costs - network	500	500	500	500	500	500	500	3500	
Per patient costs - install	900							900	800+800/8
Per patient costs - support	3300	3373	3447	3522	3600	3679	3760	24681	1*15.14*1*52+1*16.11*3*52=787+2513
Per patient costs - discharge								0	
Other - maintenance	450	450	450	540	540	540	540	3510	Training, maintenance & annual overhaul
Total outflow	10850	4523	4597	4762	4840	4919	5000	39491	
Savings - in-patient								0	
Savings - emergency dep.								0	
Savings - home visits								0	
Savings - primary care	6600	6745	6894	7045	7200	7359	7521	49364	1*15.14*2*52+1*16.11*6*52=1575+5025
Savings - long term care								0	
Other								0	
Cost savings	6600	6745	6894	7045	7200	7359	7521	49364	
Net annual cashflow	-4250	2222	2297	2283	2360	2440	2521	9873	
Net cumulative cashflow	-4250	-2028	269	2552	4912	7352	9873	9873	

Note: This cash flow analysis is calculated based on the following assumptions:

(1) The main financial beneficiary of Scenario 3 is the owner of the care home or nursing home.

(2) The one-time cost of the hardware "iStander + activLife" is €5,500 (i.e., each older individual gets one iStander in his/her room to assist their ADLs and eight older adults share one activLife Platform for physical and cognitive training).

(3) In traditional care home scenario, it is assumed that without the proposed system, one physical therapist needs to work for two hours per week and another primary

caregiver needs to work for six hours per week for taking care of one patient. Using the proposed solution, one physical therapist needs to only work for 1 hour and one primary caregiver only need to work two hours each per week to assist the rehabilitation of the patient.

(4) A 2.2% annual salary increase is considered.

(5) Same as previously mentioned, it is assumed that the hourly cost of a physical therapist is €15.14 and of a primary caregiver is €16.11.

According to the cash flow analysis, the key financial indicators of Scenario 3 can be calculated, see Table 4-15.

Table 4-15: Key financial indicators of Scenario 3

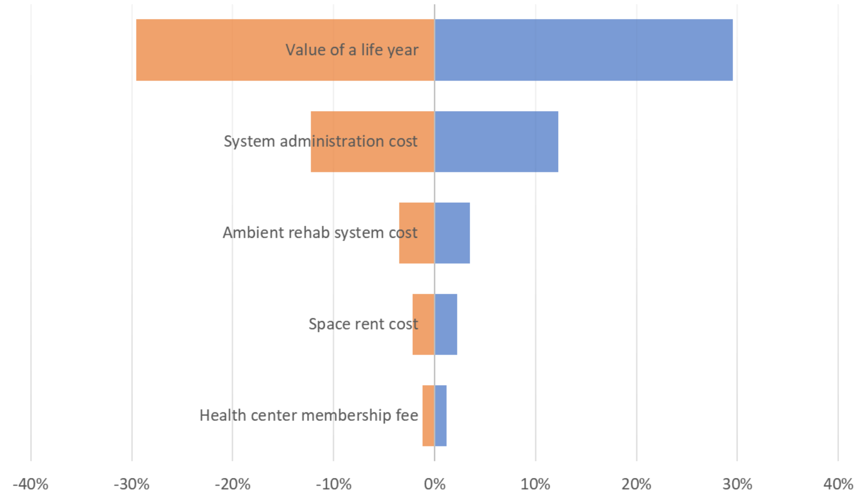
Key financial indicator	Value
Benefit–Cost Ratio (BCR)	1.25
Return on Investment (ROI)	25.00% (over 7 years)
Payback Period (PBP)	2.9 years or 35 months
Initial Investment Value (IIV)	€6,400
Net Present Value (NPV)	Applicable when interest rate is positive

As indicated in Table 4-15, the ROI of Scenario 3 is 25.00% over seven years per set of devices (i.e., one iStander and 1/8 activLife Platform). The PBP is three years or 35 months. The IIV is €6,400 per set of devices. The NPV is also not considered due to the reason mentioned above (i.e., negative discount rate in Germany).

4.4.4.4 Sensitivity analysis

Like in Case Study I, a simple sensitivity analysis is conducted, regarding several major variables in the cash flow analysis. By adjusting each input variable 10% better and 10% worse, the total accumulative cash flow by the end of the seven-year period will also change accordingly. Thus, the increase and decrease of total accumulative cash flow, compared to the original estimation, can be calculated. In this sensitivity analysis, variables such as labor hourly rate, Ambient Rehabilitation Kit cost, and annual wage increase rate were evaluated.

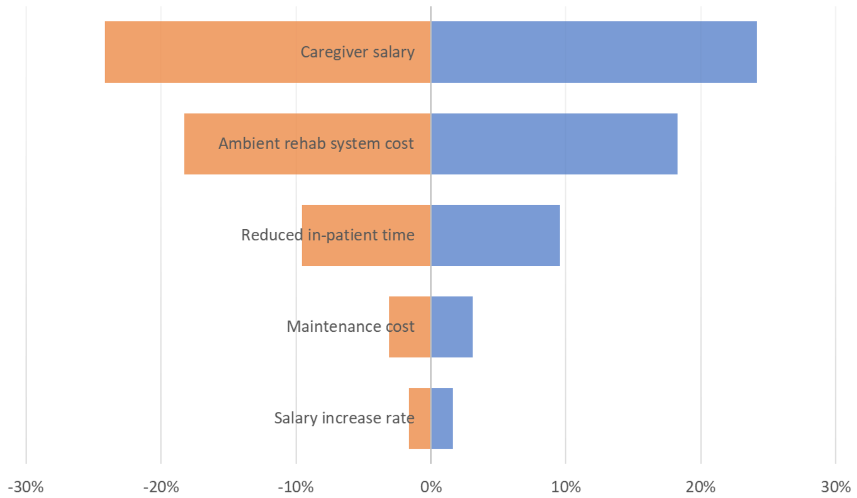
Specifically, in Scenario 1, variables including value of a life year, system administration cost, Ambient Rehabilitation Kit cost, rent cost, and health center membership fee were examined. It can be observed that in the home and community aging scenario, the value of a life year is the most impactful variable (see Figure 4-13). Although the real value of human life cannot be measured by money, it is fair to say that the ambient rehabilitation for home and community aging can bring greater benefits in countries and regions where the value of a life year is higher. In addition, the health center membership contribution is insignificant compared to other variables. Therefore, the community can consider to reduce or waive the contribution fees in order to maximize the participation of older residents.



	Health center membership fee	Space rent cost	Ambient rehab system cost	System administration cost	Value of a life year
Positive	1%	2%	4%	12%	30%
Negative	-1%	-2%	-4%	-12%	-30%

Figure 4-13: Sensitivity analysis of Scenario 1

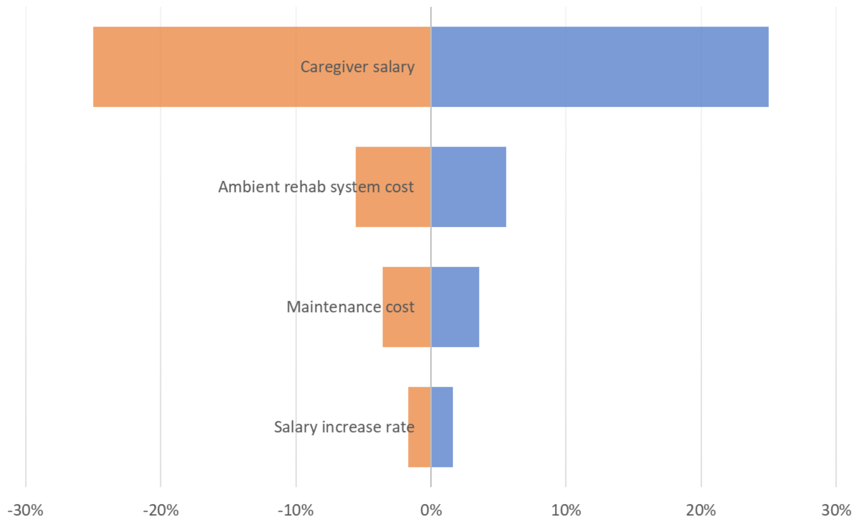
In Scenario 2, variables such as caregiver salary, Ambient Rehabilitation Kit cost, reduced inpatient time, maintenance cost, and salary increase rate were examined. As shown in Figure 4-14, caregivers’ salary is the most impactful variable, followed by the Ambient Rehabilitation Kit cost. As a result, as the salary of caregivers increases and the hardware cost reduces over time, the economic performance of the Ambient Rehabilitation Kit in the hospital environment will be even better.



	Salary increase rate	Maintenance cost	Reduced in-patient time	Ambient rehab system cost	Caregiver salary
Positive	2%	3%	10%	18%	24%
Negative	-2%	-3%	-10%	-18%	-24%

Figure 4-14: Sensitivity analysis of Scenario 2

In Scenario 3, variables such as caregiver salary, Ambient Rehabilitation Kit cost, maintenance cost, and salary increase rate were examined. Similar to Scenario 2, caregivers' salary influences the result the most, which means that the Ambient Rehabilitation Kit in care homes can bring greater benefits in countries and regions with higher caregivers' salary.



	Salary increase rate	Maintenance cost	Ambient rehab system cost	Caregiver salary
Positive	2%	4%	6%	25%
Negative	-2%	-4%	-6%	-25%

Figure 4-15: Sensitivity analysis of Scenario 3

4.4.4.5 Recommendations

The results of key financial indicators show that the BCRs of three scenarios are 1.48, 1.28, and 1.25 respectively, all exceeding 1. Therefore, the Ambient Rehabilitation Kit overall can be recommended to the key beneficiaries (e.g., townships and municipalities, rehabilitation hospitals, care homes) in various scenarios in Germany.

Unlike Case Study I whose key beneficiary is a large corporation that operates globally, the primary beneficiaries of the three scenarios in Case Study II all operate locally in Germany. Moreover, the labor cost of caregivers in each country can vary vastly from informal to formal caregivers, and from rural to urban areas. Therefore, the BEP of all three scenarios based on caregiver salary are not calculated. The feasibility of implementing the Ambient Rehabilitation Kit in each country or region needs to be carefully studied individually.

4.4.5 Discussion

This case study applies the proposed framework for the CBA of robotic and automated systems to evaluate the Ambient Rehabilitation Kit proposed in this thesis. The results indicate that the Ambient Rehabilitation Kit is financially worth in Germany, which answers SQ3 (i.e., what is the financial performance of the proposed system?). The advantages and future validation of the methods, as well as the additional socio-environmental implications, limitations, adaptability, and reproducibility, are further discussed in the sections below.

4.4.5.1 Advantages and future validation of the methods

This case study mainly discusses the direct economic implications of smart furniture, using the PI^{2}U solutions developed in the REACH project as case studies. It will be one of the first CBA research instances focusing on smart furniture, setting a valuable precedent for the field of elderly-oriented smart home.

The method is practical and helpful for the key beneficiaries to make decisions about whether to invest in smart furniture technology, without the need of large amount of data. The calculation method is specifically designed to estimate the costs and benefits of an advanced care solution. Therefore, it does not require a large amount of time and effort of the key beneficiary, such as historical data collection and opinion survey.

4.4.5.2 Limitations

This initial CBA is by no means an impeccable process. The results reported in this section has certain limitations that are summarized as follows.

(1) The CBA is conducted for German beneficiaries based on Germany's market and healthcare system. The results might not fully apply to other countries.

(2) The usability of each scenario needs to be further tested and validated in relevant environments.

(3) Some data are only estimations. More accurate data are needed in the future.

(4) The manufacturing cost is only calculated based on prototyping cost in Germany's

market, thus cheaper alternatives such as outsourcing in lower-income countries are not considered. Also, if the production volume increases in the future, the price of the system might be substantially lower.

4.4.5.3 Further implications

This CBA mainly calculated the direct financial indicators of the Ambient Rehabilitation Kit in three scenarios in Germany. Admittedly, there are limitations in this case study. However, other implications of the CBA are worth noting here.

(1) Based on the CBA, it can be concluded that smart furniture solutions developed in this project are in general worth investing by hospitals, care homes, and overall healthcare system in Germany.

(2) Given that the assumptions for CBA made here are relatively conservative, as the production number increases and manufacturing cost lowers over time, it is expected that the cost can reduce further.

(3) Due to the lack of research on the CBA of smart furniture solutions for aging society, the results of this CBA will provide first-of-its-kind insights for the wise use and efficient allocation of smart healthcare resources in aging society.

(4) This CBA only calculated mostly the direct benefits of the Ambient Rehabilitation Kit. More importantly, other social benefits of the proposed system that were not directly calculated here are also worth mentioning, such as improved quality of life, and liberated productivity from both formal and informal caregivers.

(5) When transferring the developed technology to other markets outside Germany, the corresponding CBA based on the local market and situation will be necessary.

(6) Furthermore, researchers and entrepreneurs beyond the REACH project can also benefit from the proposed methodology to conduct their CBA of smart furniture and smart home solutions for various scenarios in aging society.

5 Towards an elderly-oriented smart furniture solution in China: A survey and an action plan (Act)[9]

"The world is a sphere. There is no East or West."

Ai Weiwei[10]

Even if an innovation proves to be beneficial and profitable, another key to the success of the technology is user willingness and acceptance. The abovementioned CBA of the Ambient Rehabilitation Kit proved that the system overall can be recommended to the key beneficiaries (e.g., townships and municipalities, rehabilitation hospitals, care homes) in various scenarios. However, in order to better scale up the innovation to reach a broader audience, the users' willingness to adopt the technology in global key markets needs to be investigated before entering these markets. This chapter attempts to investigate older adults' attitudes and opinions towards the elderly-oriented smart furniture and relevant technologies in potentially one of the most important markets for gerontechnology products in the coming years.

Population aging is one of the major challenges facing the world. In particular, the advent of China's aging society caused by various factors will be a major threat to its future development. Therefore, serious measures need to be taken to achieve its demographic sustainability. Smart furniture can be considered as a novel subcategory of gerontechnology. One of the major outcomes of the EU-funded REACH project was a series of smart furniture pieces named PI^2Us which focus on promoting the health and activity level of older adults (Hu et al., 2020a). This outcome can potentially be a solution to mitigate the consequences caused by population aging. However, users' willingness to participate in using such systems remains a major challenge (Sun et al., 2009). In order to understand the attitudes and opinions of Chinese older adults towards the smart home and smart furniture technology, the authors conducted an opinion survey using the PI^2Us as an example, which sampled more

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[9] This chapter is partially based on the conference paper entitled "Towards a Distributed Intelligent Home Based on Smart Furniture for China's Aging Population: A Survey" (Hu et al., 2021b) published in the Proceedings of 38th International Symposium on Automation and Robotics in Construction (ISARC 2021) and has been reused here with the permission of the conference organizer, see appendices. The authors retain the copyright of this publication according to the publisher (see Appendix IV: Letters/statements of reuse permission from publishers). Authors' contribution: R. Hu (correspondence, conceptualization, methodology, survey design, formal analysis, visualization, data curation, writing-original draft preparation, writing-review and editing), T. Linner (conceptualization), S. Wang (data curation), W. Cheng (data curation), X. Liu (data curation), J. Güttler (conceptualization), C. Zhao (data curation), Y. Lu (review, supervision), T. Bock (conceptualization, supervision). The content of this chapter will be considered for further publication in a peer-reviewed academic journal (e.g., Smart and Sustainable Built Environment).

[10] Ai Weiwei (1957-): Chinese artist.

than 380 older adults in 26 out of 34 provincial-level administrative divisions of China. The survey showed that Chinese older adults in general have a highly positive attitude towards smart furniture. Several other insights were also revealed from the survey. Based on further in-depth analyses, the chapter summarized why elderly-oriented smart furniture has the potential to thrive in China's market soon. Finally, a three-year project action plan for developing localized elderly-oriented smart furniture technology in cooperation with a large Chinese furniture manufacturer was proposed.

5.1 Introduction

Population aging is one of the major challenges not only facing the developed countries, but also threatening many emerging economies. Specifically, China's upcoming aging society caused by various factors will pose an imminent threat to its future development. Therefore, a variety of measures must be taken to achieve its demographic sustainability. Smart home technology has gained substantial popularity over the past decade. It also started to show its prominence in the fields of aging in place and home care for older adults. Smart furniture can be considered as a novel subcategory of smart home technology. However, gerontechnology research in China is still lagging behind compared to developed countries such as USA, Germany, and Japan. Specifically, according to a study in 2015, China was still considered as an academic laggard in gerontechnology compared to leaders such as USA and UK, although it began to catch up in most recent years (Huang et al., 2015). At the same time, there is also a lack of research on the adoption of gerontechnology among Chinese older adults. Therefore, to conduct a survey to investigate their adoption, attitude, and preference for smart home and smart furniture technology will be helpful for the future implementation of these technologies. In the following sections, the opinion survey will be introduced, and its implications will be analyzed. Finally, a project action plan for implementing elderly-oriented smart furniture technology in China will be illustrated.

5.2 Survey methods

In this section, a smart furniture solution developed in the EU-funded research project REACH for the purpose of increasing the activity and independence level of older adults is introduced. Furthermore, based on the smart furniture solution developed in REACH, the opinion survey to investigate the attitude of Chinese older adults towards using smart furniture technologies is detailed.

5.2.1 Smart furniture in context

The smart furniture devices exemplified in the context of this chapter were developed in the REACH project, a large European interdisciplinary research project aiming at developing customized healthcare systems to promote older adults' activity level and independence (see Chapter 3). In REACH, a special type of smart furniture named PI^2U was developed, which seamlessly integrated the required functions (e.g., unobtrusive sensing and monitoring, training/gaming, nutrition, AI assistant, etc.) into the different living environments. The development process of the PI^2Us (including but not limited to SilverArc, MiniArc, SilverBed, ActivLife, see Figure 5-1) adopted iterative design principles on both hardware and software levels, which allows the project team to optimize the products through prototyping, testing, analyzing, and refining.

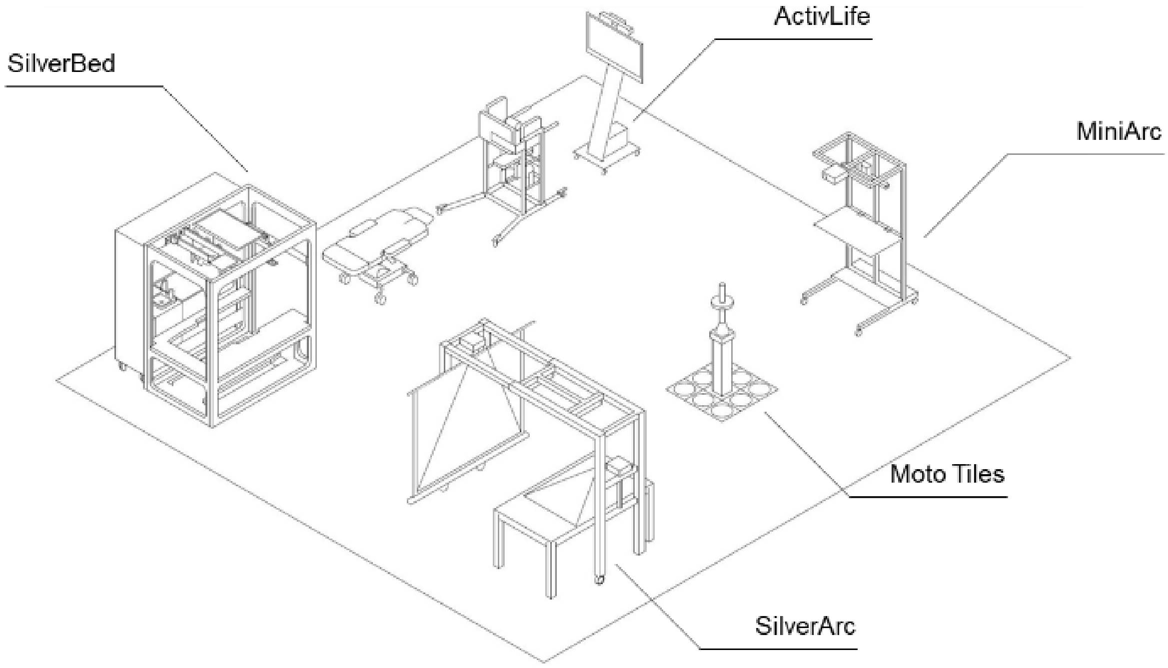


Figure 5-1: Various PI²Us developed in the REACH project

Furthermore, based on various PI²Us, a modularized smart home solution, namely the Ambient Rehabilitation Kit concept was proposed, integrating PI²Us and key technologies in REACH to create a complete interior living and care environment for older adults in different living environments such as home, hospital, and community (see Figure 5-2).

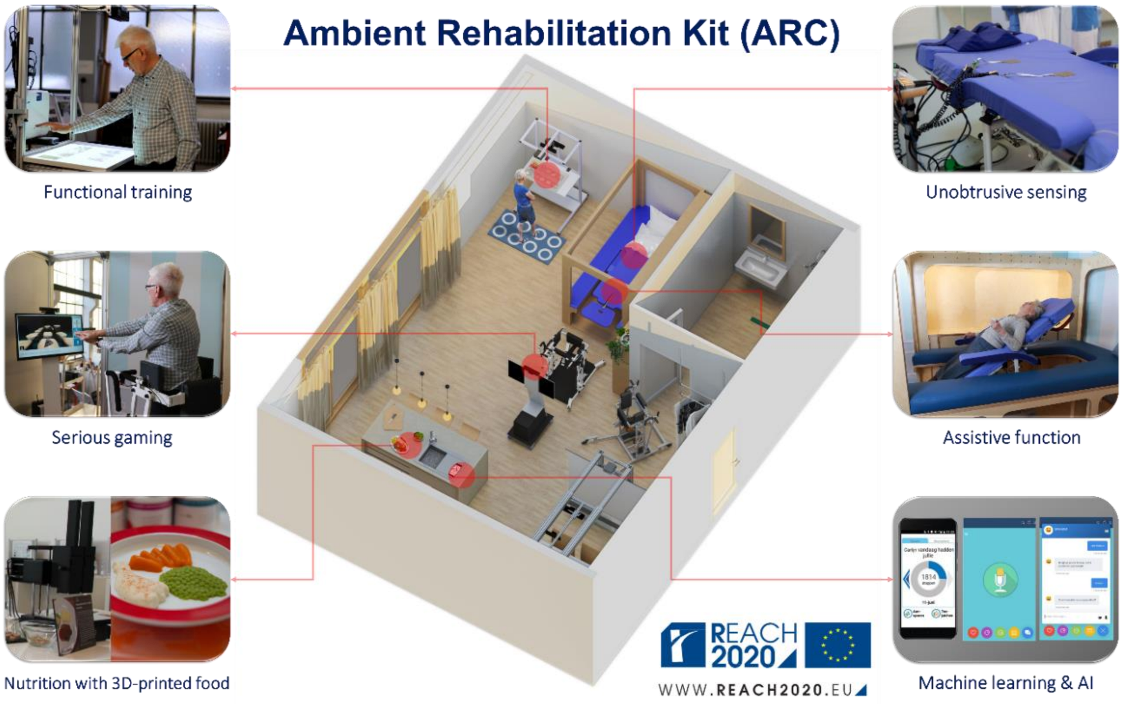


Figure 5-2: The Ambient Rehabilitation Kit concept including real-life testing of the PI²Us

5.2.2 Opinion survey

In this section, the opinion survey to investigate the attitudes and opinions of Chinese older adults towards using smart furniture technologies based on the PI²Us as an example is introduced. The survey was conducted via two main channels (e.g., mainly via WeChat app on smartphones and email links, and in-person questionnaires as a supplement for users who do not use any smartphones or tablets). With over one billion active users only in China, WeChat provided an excellent platform to distribute the questionnaires.

The survey consisted of 11 close-ended questions related to the current situation of the participants and their opinion towards the smart furniture and relevant technologies for older adults. In particular, photos with descriptions of older adults using the PI²Us were shown as an example of smart furniture to give the survey participants an intuitive impression of the appearance and functions of the PI²Us. The questions were designed with principles of simple language, common concepts, manageable tasks, and widespread information (Converse and Presser, 1986). Table 5-1 shows the 11 questions in the questionnaire.

Table 5-1: List of survey questions

No.	Question
01	What year were you born?
02	What is your gender?

03	What area are you currently living?
04	What is your highest level of education (including enrollment)?
05	Where is your main place of residence?
06	Which of the following smart digital products have you used?
07	Which of the following smart home devices have you used?
08	What do you think is the ease of use of current technology products for older adults?
09	How interested are you in using smart furniture with health functions? (Examples from the REACH project are given.)
10	How important are the following attributes to you for using smart furniture?
11	What do you think of the prospects of China's elderly-oriented smart furniture market?

Powered by Tencent Questionnaire (https://wj.qq.com/), the survey was designed in a user-friendly manner in order to appeal to older adults - the main audience of this survey. The survey was kept short as much as possible, which can be easily finished by older adults in 3-5 minutes. The survey was pre-tested with several older adults before formerly sending out in order to optimize the understandability and order of the questions.

Here are some screenshots to show the simplicity and elderly friendliness of the survey interface on mobile devices (see Figure 5-3).

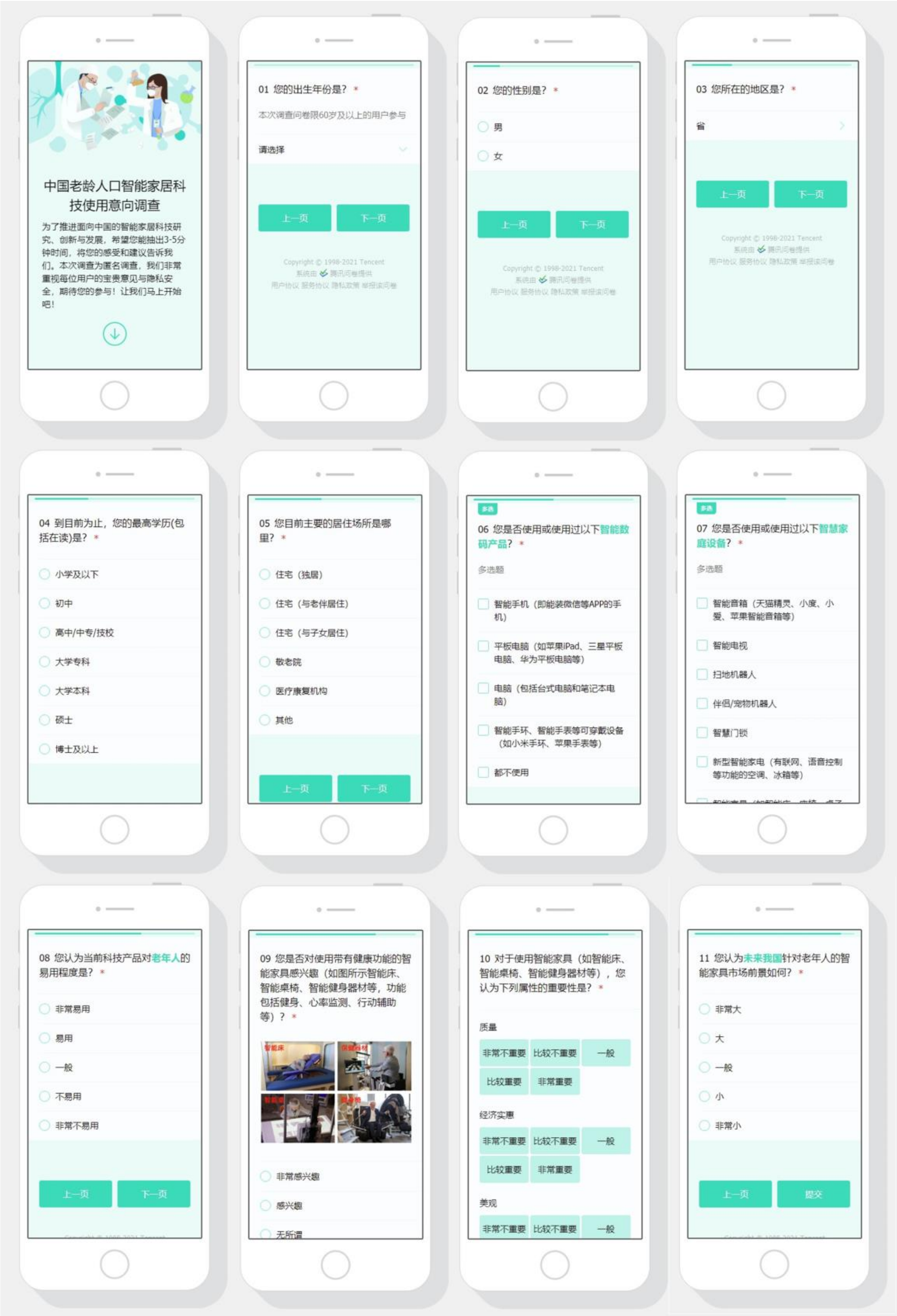


Figure 5-3: Screenshots of the simple and practical survey interface customized for older adults (in Chinese)

5.2.3 Good practice for protecting individual privacy in the survey

Once individuals' data is involved, protecting their data privacy will be critical. Therefore, the good practice for protecting individual privacy in the survey is reported as follows. First and foremost, the survey was conducted in a fully anonymous manner, meaning that information such as names, birth dates, addresses, and resident identity card numbers were not collected. This approach excludes any possibility to identify any individual survey participant. Furthermore, in order to participate in the online survey, all the participants needed to give consent to provide their basic demographic information such as age, gender, province of residence, and level of education. In addition, the data collected from older Chinese citizens was stored in the server of Tencent within the territory of the People's Republic of China during the research, which was in line with the newly established Data Security Law of the People's Republic of China. After the analysis was completed, the data collected in this survey was securely deleted in the user account, which according to Tencent Questionnaire's user account policy means permanent erasure in the company's server. These measures are also in line with Guide on Good Data Protection Practice in Research (European University Institute, 2019).

5.3 Survey results

The survey lasted for 45 days from January 7th, 2021 till February 20th, 2021. In total, 1313 questionnaires were sent out and 403 responses were collected, of which 384 were valid, leading to an effective return rate of 29.2%. 19 responses were removed due to reasons such as incomplete data. The average completion time for each participant was 4 minutes and 17 seconds, which well met the expectation for the questionnaire design. The vast majority of the older survey participants completed the survey without issues. Necessary guidance or explanation were provided to the participants if needed. The results of the survey are revealed in detail as follows, including the general analysis and cross analysis.

5.3.1 General analysis

As mentioned above, 384 older adults from 26 out of the total 34 provincial-level administrative divisions of China provided valid questionnaires during the survey. Figure 5-4 shows the survey participants' distribution in each provincial-level administrative division. As of the beginning of 2021, there are approximately 260 million Chinese older adults aged 60 and over (People's Daily Online, 2021). Therefore, it can be calculated that the survey can represents the Chinese older population with a margin of error (MOE) of ±5%, which is acceptable for categorical data in social research (Bartlett et al., 2001).

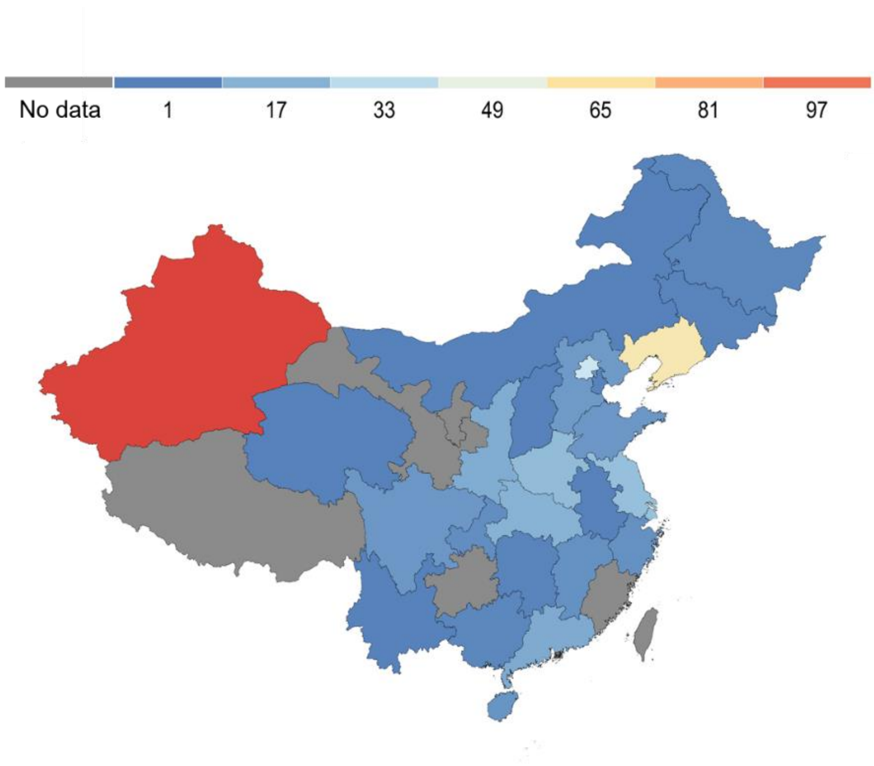


Figure 5-4: Heat map showing the valid survey sample size in each provincial-level administrative division of China

There are many ways to categorize older adults by age. One study differentiated them as the young old (60-69), the middle old (70-79), and the very old (80+), which is suitable for this study (Forman et al., 1992), because the current retirement age in China is 60 for male employees and 55 for female employees. The average age of the survey participants was 68.64 years old. Among these participants, 39.1% were male and 60.9% were female. Figure 5-5 shows the age (left) and gender (right) distribution of the survey participants

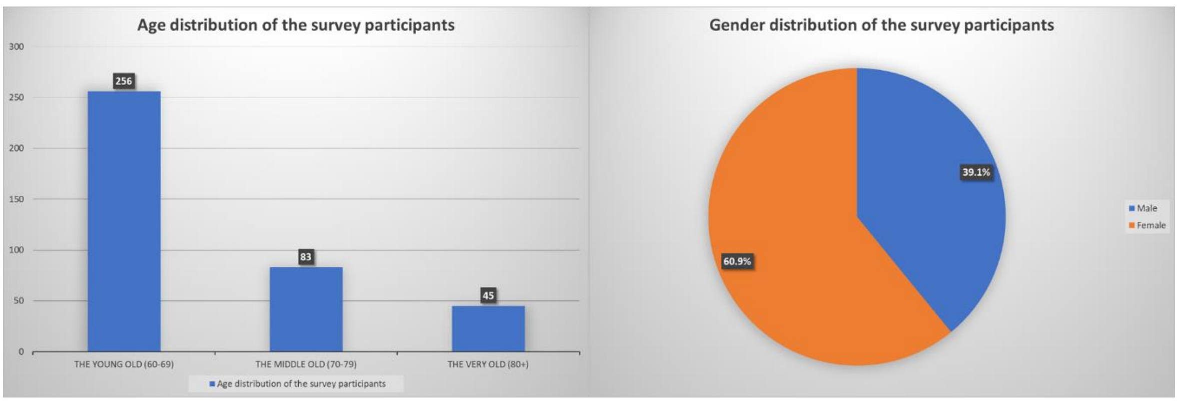


Figure 5-5: Demographics of survey participants (left: age distribution; right: gender distribution)

In general, the education level of the survey participants was relatively balanced, among which 49.5% had college degree or above (e.g., junior college, bachelor's, and master's degree) and 50.5% had high school education or below (e.g., primary school, junior high school, high school/secondary vocational school) (see Figure 5-6 left).

Regarding the places of residence, 75.2% of the survey participants lived either alone or with spouse, and 20.8% of them lived with their children. Only 0.8% of them were living in retirement homes or nursing homes (see Figure 5-6 right). This phenomenon is likely because 1) over 90% of Chinese citizens own their homes (Kharas and Dooley, 2020), and 2) in Chinese culture, aging in place (i.e., aging in home and community) is a common practice, and older adults tend to rely on family members for primary care in later life due to the cultural norm of filial piety (Bai et al., 2020), although living in retirement homes has started to pick up momentum in recent years.

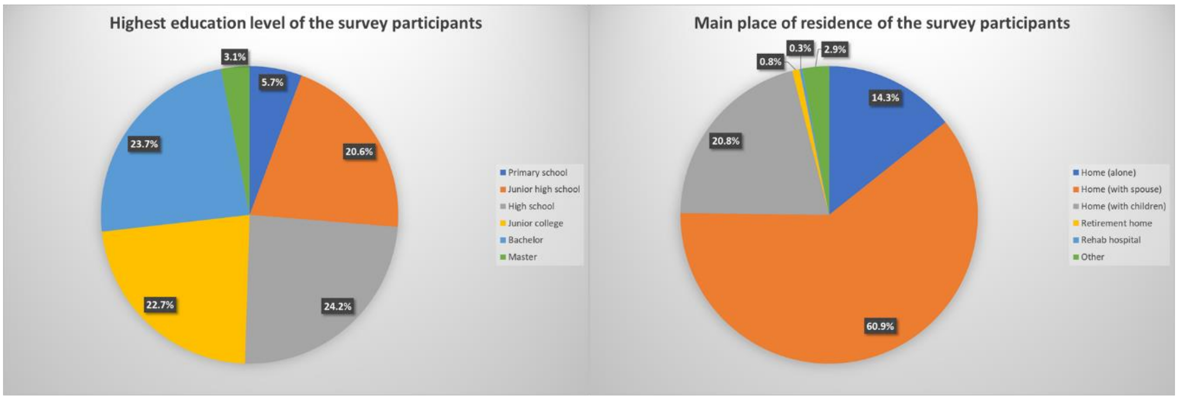


Figure 5-6: Education level and main place of residence of survey participants

Regarding the user adoption rate of personal smart devices (e.g., smartphones, tablets, PCs/laptops, wearables), 93.5% of the participants used smart phones. On the contrary, only 8.9% of them used wearables (e.g., Mi Band, Fitbit, Apple Watch, Samsung Galaxy Fit), see Figure 5-7. A possible explanation could be the inadequate functionality and frequent need for charging for current wearables. For example, one older adult from the survey complained that "the functions of the smart band are very limited, but it requires charging the battery every now and then. Therefore, it is a burden to use, so I abandoned it." This phenomenon also suggests that the ambient sensing solution integrated in smart furniture could provide a good alternative to wearables. In this survey, 5.5% of the participants did not use any of these devices. Although admittedly, it is likely that older adults who did not use personal smart devices were under-sampled because the majority of the questionnaires were completed via WeChat app with a few exceptions of guided questionnaires, it is fair to say the adoption rate of personal smart devices among Chinese older adults is satisfactory.

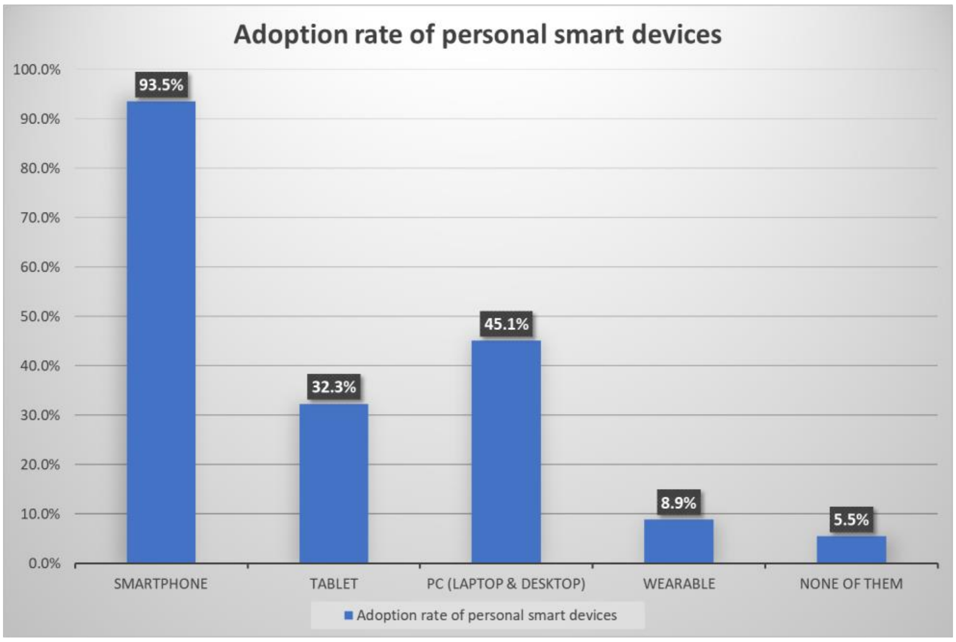


Figure 5-7: Adoption rate of personal smart devices

In the next question of user adoption of smart home devices (e.g., smart speaker, smart TV, robot vacuum, pet robot, smart door lock, smart appliance, smart furniture, etc.), three quarters of the participants had experience with at least one of them, with smart TV having the highest adoption rate of 49.5%. On the contrary, smart furniture had the second lowest user adoption rate of 3.1% (only higher than companion robots, see Figure 5-8). This is mainly because smart furniture is relatively a new field without many mature applications on the market. On the other hand, however, it also indicates a substantial market potential.

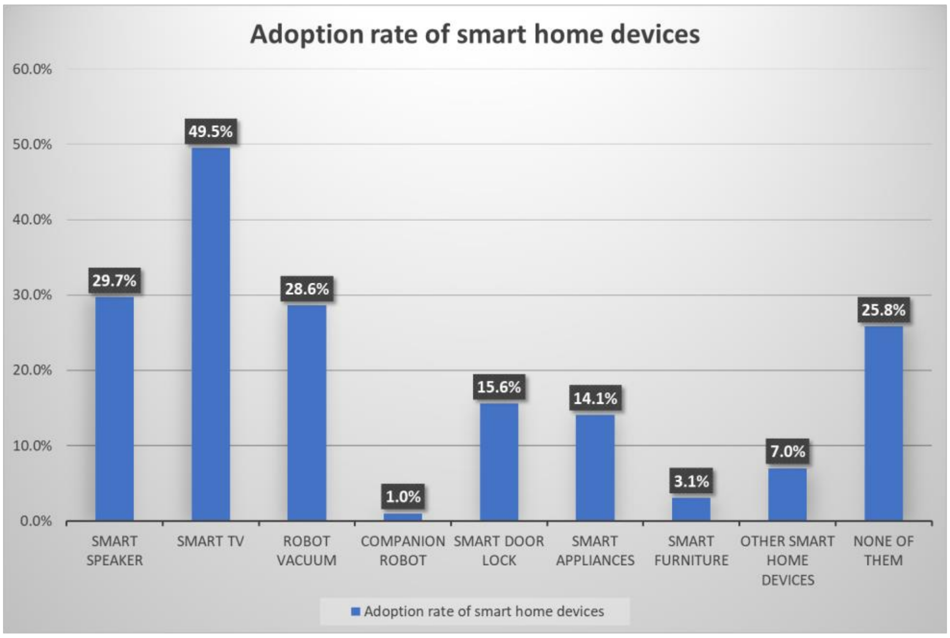


Figure 5-8: Adoption rate of smart home devices

Regarding the usability of today's technology products for older adults, only 45.3% of the participants thought that they were easy or very easy to use (see Figure 5-9). Therefore, improving the usability for older adults is highly important for developing new or improving current technology products.

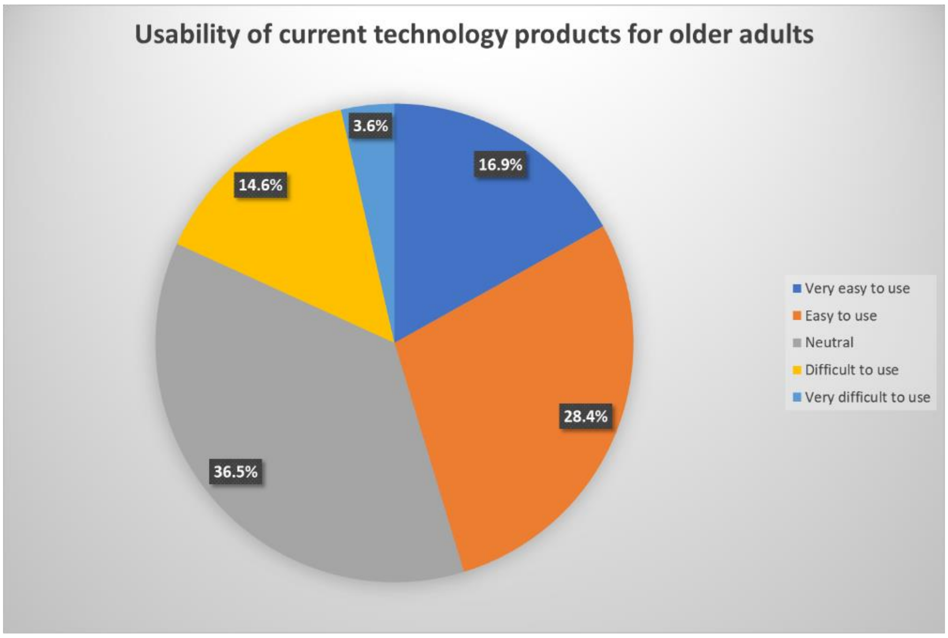


Figure 5-9: Usability of current technology products for older adults

When the survey participants' interest in using elderly-oriented smart furniture was asked, examples of four PI²U prototypes from the REACH project were given. As a result, 60.9% of the participants are interested or very interested in using elderly-oriented smart furniture (i.e., PI²Us). This indicates substantial interest and market opportunities for smart furniture among Chinese older adults (see Figure 5-10).

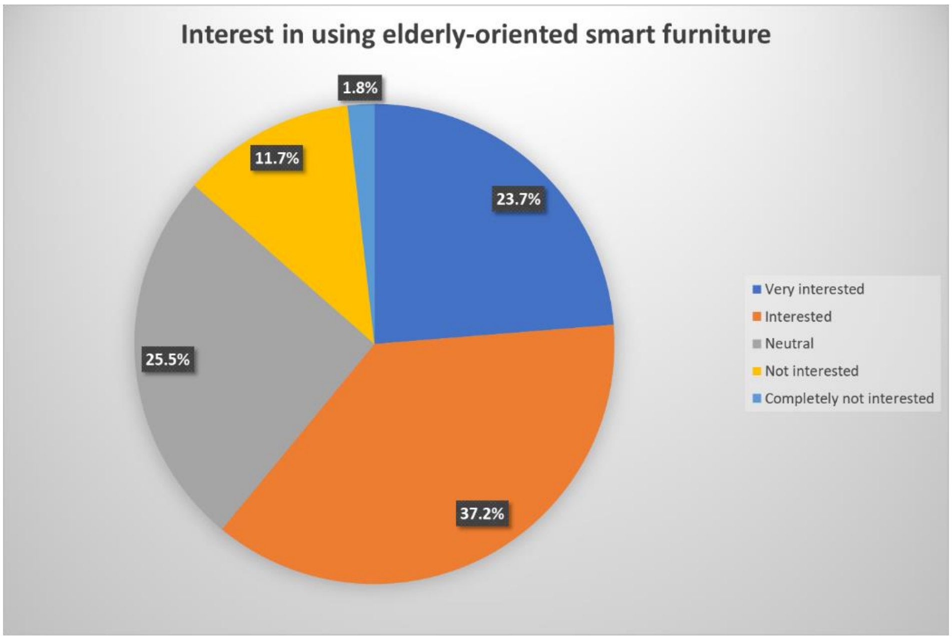


Figure 5-10: Interest in using elderly-oriented smart furniture

In terms of the importance of various attributes in smart furniture, the survey participants valued the safety of the products the most (i.e., 85.4% of the participants find it important or highly important), followed by usability (i.e., ease of use, 77.8%), quality (75.5%), privacy protection (73.4%), affordability (70.6%), multifunctionality (50%), and the aesthetics the least (48.2%). This result indicates that when developing elderly-oriented smart furniture products for Chinese older adults, more attention shall be paid to aspects such as safety, ease of use, quality, privacy protection, and affordability, while aesthetics and multifunctionality are relatively of less importance. See Figure 5-11 for specific statistics.

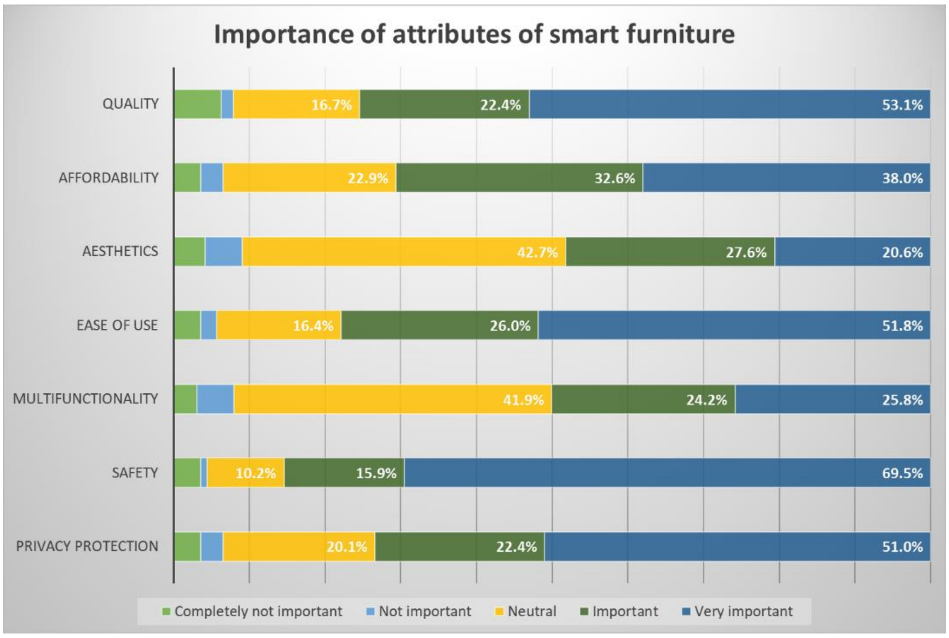


Figure 5-11: Importance of attributes for smart furniture

Regarding the final question, a vast majority (i.e., 73.7%) of the participants think that there will be a substantial market potential for elderly-oriented smart furniture in China, which further verifies the inference above (Figure 5-12).

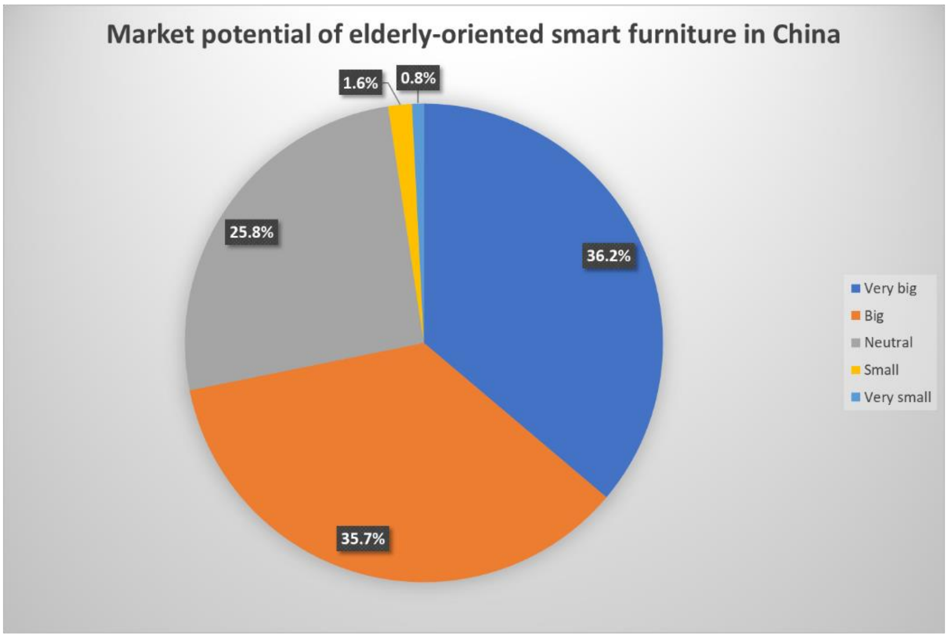


Figure 5-12: Market potential of elderly-oriented smart furniture in China

5.3.2 Cross analysis

This section focuses on analyzing the correlation between participants' demographics (e.g., age, gender, education level) and attitude towards smart home and smart furniture technology. The statistics were tested by Pearson's chi-squared test ($n \geqslant 40$) to evaluate the statistical significance between any two groups (Cochran, 1952; Gravetter and Wallnau, 2013).

5.3.2.1 Age and adoption rate, difficulty, interest, and expectations

As shown in Figure 5-13i, there is a sharp decline in smart home technology adoption rate when the participants are older. In the "young old" group, 84.0% of the participants had experience in least one smart home product, while in the "very old" group, only 35.6% had experience in using any smart home technology. Using Pearson's chi-squared test, the differences between any two age groups are extremely significant ($p < 0.01$).

Regarding the correlation between age and difficulty in using technology products (Figure 5-13ii), only around 15% of the older adults in both "young old" and "middle old" groups found it difficult or very difficult to use technology products ($p > 0.05$). However, the percentage is significantly higher in the "very old" group compared to the first two age groups ($p < 0.01$).

Regarding the correlation between age and interest in using elderly-oriented smart furniture (Figure 5-13iii), more than 60% of older adults in the "young old" and "middle old" groups were interested or very interested in using the smart furniture developed in the REACH project. The percentage dropped slightly to 46.67% in the "very old" group, but still was close to half of that group. However, no statistical significance can be observed between the "very old" group and other two age groups regarding user interest ($p > 0.05$). Therefore, the overall interest in using smart furniture is strong among Chinese older adults.

Regarding the correlation between age and expectations in elderly-oriented smart furniture technology (Figure 5-13iv), all three groups of older adults expressed high expectations for its future market potential. The differences between three groups are not statistically significant ($p > 0.05$).

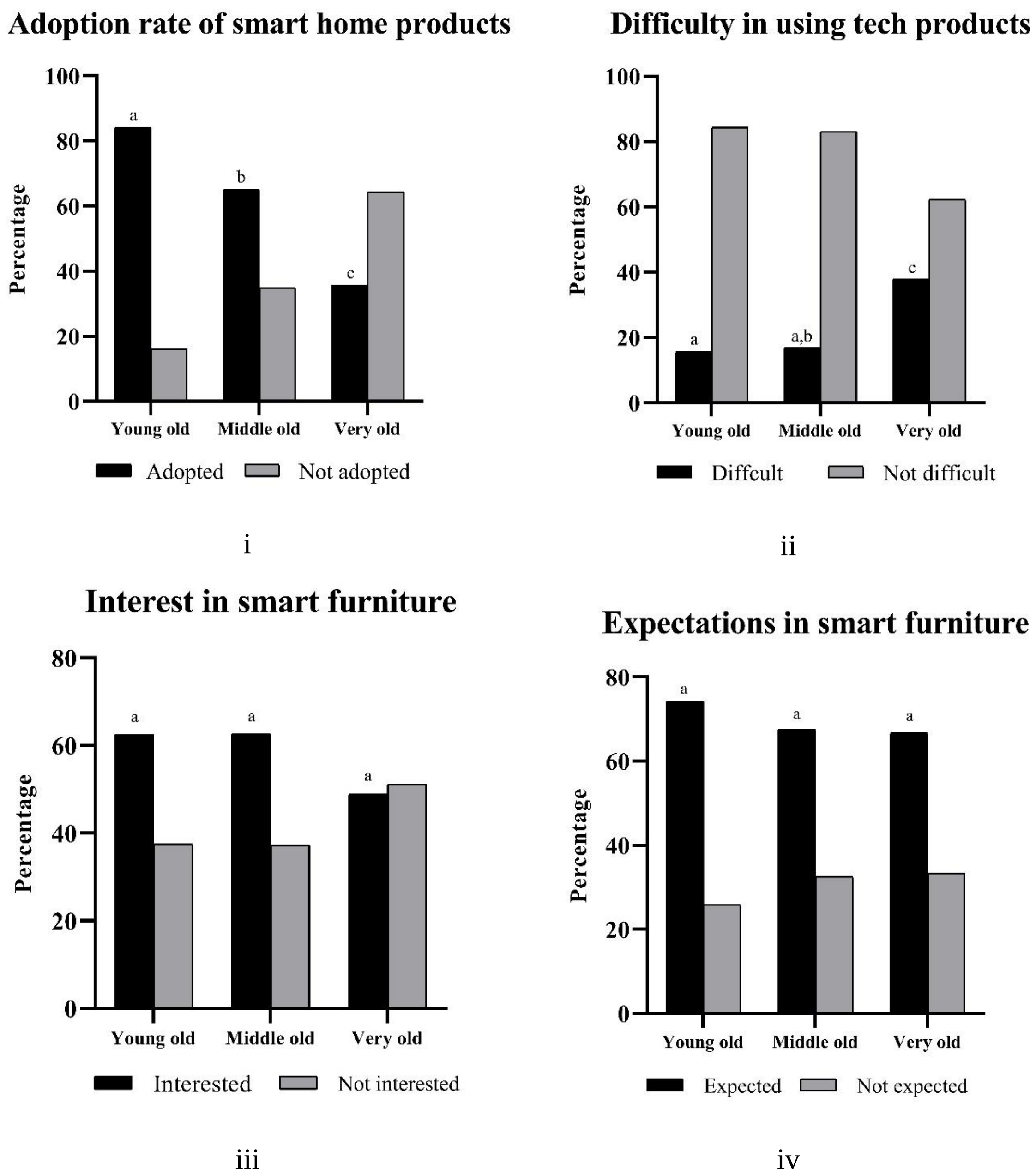


Figure 5-13: Correlation between age and smart home technology adoption rate (the difference between any two groups sharing the same letters is not statistically significant)

5.3.2.2 Gender and adoption, difficulty, interest, and expectations

As shown in Figure 5-14, it is impossible to observe statistically significant differences in the adoption rate of smart home technology, difficulty, interest as well as expectation in elderly-oriented smart furniture between different genders ($p > 0.05$). Male participants seem to have slightly more difficulty in using technology products, although the difference is not statistically significant ($p > 0.05$).

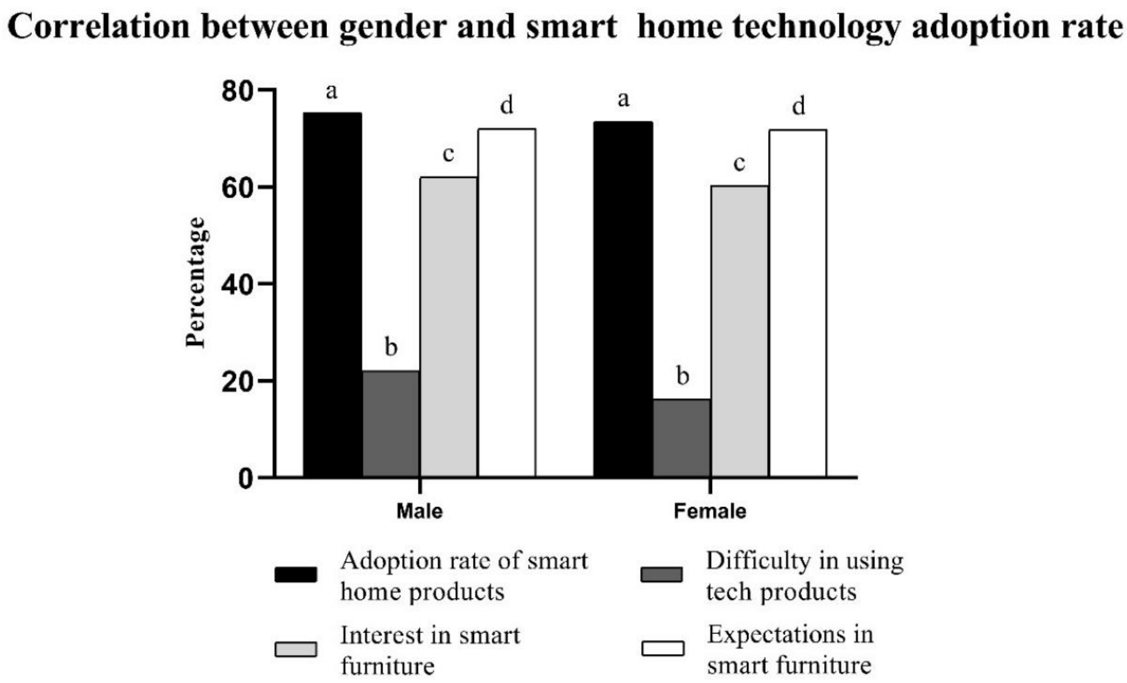
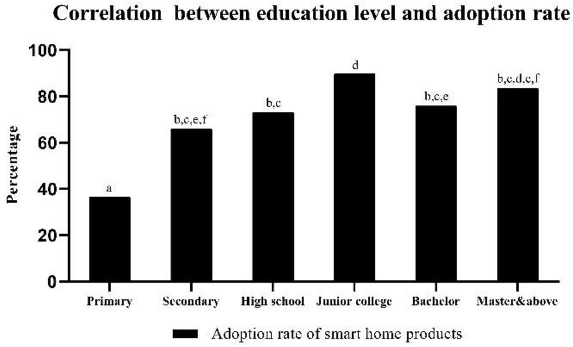


Figure 5-14: Correlation between gender and smart home technology adoption rate (the difference between any two groups sharing the same letters is not statistically significant)

5.3.2.3 Education level and adoption rate, difficulty, interest, and expectations

As indicated in Figure 5-15i, older adults with primary school education have significantly lower adoption than those with any other education levels ($p < 0.05$). Regarding the correlation between education level and difficulty in using technology products (Figure 5-15ii), older adults with education level lower than high school find it significantly more difficult than those with junior college education ($p \leqslant 0.01$). Meanwhile, participants with junior college education have significantly higher interest in using elderly-oriented smart furniture than those with high school education or below ($p < 0.05$) (Figure 5-15iii). Finally, the majority of most education groups (expect for secondary school) have high expectations for elderly-oriented smart furniture (Figure 5-15iv). In particular, older adults with junior college education or above have significantly higher expectations than those with secondary school education ($p \leqslant 0.01$).



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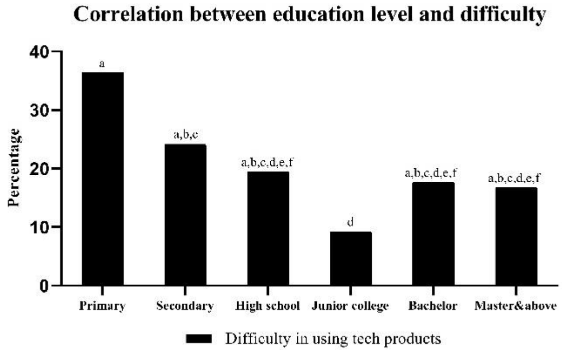

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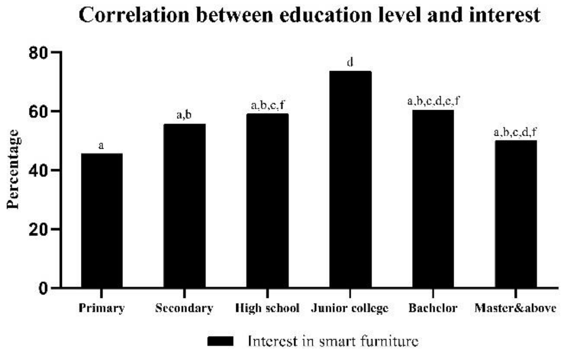

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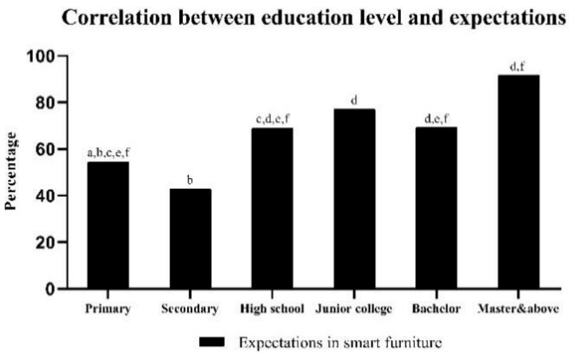

iv

Figure 5-15: Correlation between education level and adoption rate, difficulty, interest, and expectations (difference between any two groups sharing the same letters is not statistically significant)

5.4 Discussion

In this section, the implications of the survey result as well as the limitations of the survey are further discussed. In addition, the reasons why elderly-oriented smart furniture and gerontechnology in general can thrive in China are analyzed. Furthermore, a three-year project action plan for developing smart furniture technology is proposed.

5.4.1 Limitations of the survey

Although, like any other surveys, this survey has certain limitations, the conclusion will not be affected to a large extent. The main limitations are listed as follows.

- The sample size of valid participants was 384, but not substantially large compared to many other surveys. The COVID-19 pandemic limited the number of participants (especially to those of very high age) to some extent. However, the MOE of the survey still reached plus or minus 5%, which is adequate for categorical data in social science (Bartlett et al., 2001).
- The survey was conducted mainly in 26 out of 34 provincial-level administrative divisions in China. Several provincial-level administrative divisions were not covered by the survey. Furthermore, the number of older adults surveyed in each province was not exactly proportional to the population of that province.
- The female to male ratio of the survey participants was around 6:4. According to the United Nations, as of 2019 the life expectancy of Chinese citizens was 76.9. However, the life expectancy of female citizens was 79.2, and that of male was 74.8, which led to a considerable gender gap of 4.4 years of age (United Nations Development Programme, 2020). This phenomenon likely contributed to the gender imbalance of the survey participants.
- China’s current urbanization rate is at approximately 60%. The vast majority of the survey participants were from cities that vary in scale. As a result, the opinions of the rural population were not proportionally reflected. However, China is still in the process of rapid urbanization, and the urbanization rate is projected to reach 75% by 2050 (Gu et al., 2017). Therefore, the survey results are still significantly meaningful to the reality in the near future.
- The vast majority of respondents answered the questionnaire via the WeChat app on smartphones. The older adults who were not able to use smartphones were likely under sampled. In order to better reflect the opinions of older adults who do not use a smartphone, more on-site surveying after the COVID-19 pandemic will be preferred.

5.4.2 Implications of the survey results

Overall, there is a substantial amount of interest and optimism towards elderly-oriented smart furniture among Chinese older adults. Although living in retirement homes and nursing homes has started to pick up momentum, the focused application scenario for developing smart furniture technology in China shall be mainly homes due to cultural considerations. In the process of developing localized elderly-oriented smart furniture products for China, aspects such as safety, ease of use, quality, privacy protection, and affordability shall be prioritized. The digital literacy among Chinese older adults is decent but there is a clear digital gap among older adults aged 80 or over and with lower education level. As a result, it is important to close the digital gap especially for older adults over 80 years old and with lower education level using measures such as improving safety, increasing ease of use, improving quality, ensuring privacy protection, and bringing down the costs. The method of this survey is highly adaptable and scalable, and thus can be easily adopted by researchers in other regions.

5.4.3 Seven reasons why gerontechnology could thrive in China

Apart from the large amount of interest and overall optimism towards elderly-oriented smart furniture among the Chinese older adults, there are several other major reasons why smart furniture, or gerontechnology in general, could thrive in China in the near future (see Figure 5-16). The specific analysis is listed as follows.

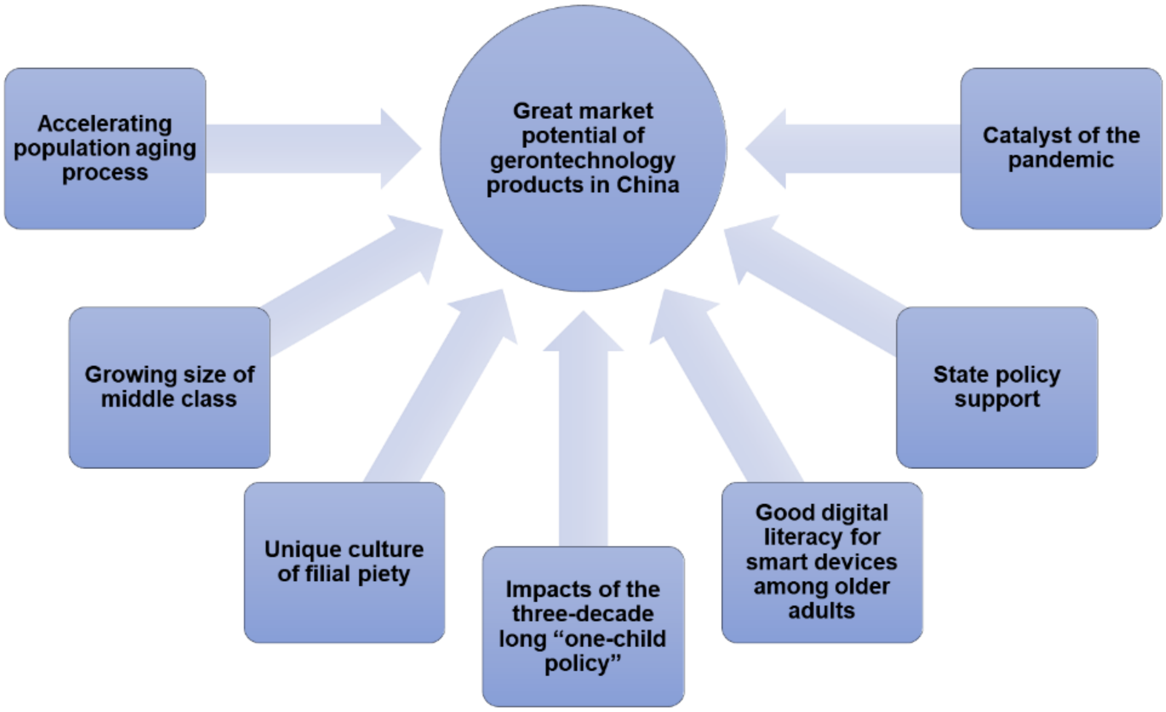

Figure 5-16: Seven reasons why gerontechnology could thrive in China

5.4.3.1 Accelerated population aging process

China is experiencing a rapid, accelerated population aging process now. According to National Bureau of Statistics, by the end of 2019, Chinese older adults aged 60 or over reached 254 million, accounting for 18.1% of the total population, which was larger than the total population of Germany and Japan combined. In the meantime, population aged 65 or over reached 176 million, making up 12.6% of the total population (National Bureau of Statistics, 2020). As mentioned in Chapter 1, “aging society”, “aged society”, and “super-aged society” respectively refers to societies where older population aged 65 years and over taking up 7%, 14%, and 21% of the total population (Kim and Kim, 2020). As a result, China is about to enter “aged society” within five years. What is worse, China is anticipated to spend the shortest time (i.e., 33 years) to transfer from “aging society” to “super-aged society” compared to major developed countries in the world, which gives it much less preparation time to brace for social impacts posed by population aging. In particular, as shown in Figure 5-17, it will only take China 23 years to transfer from “aging society” to “aged society”, and 10 years from “aged society” to “super-aged society”. In comparison, it took France 115 and 39 years respectively (R. Chen et al., 2019). Therefore, various measures must be taken to relieve the pressure of population aging, including implementing gerontechnology products to empower older adults.

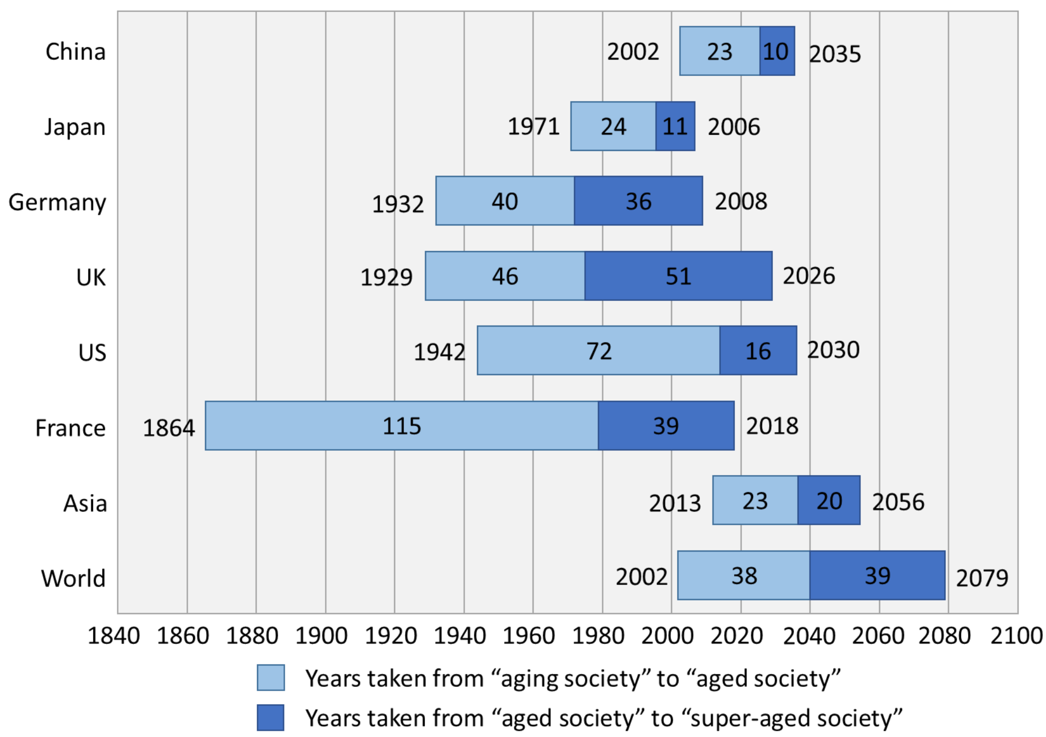

Figure 5-17: Years taken from “aging society” to “aged society”, then to “super-aged society” in different countries (diagram adopted and simplified from Chen et al., 2019)

5.4.3.2 Growing size of middle class

Today, more than 20% of world’s middle class reside in China. Moreover, it is estimated that 1.2 billion Chinese people will be considered as middle-class by 2027 (Kharas and Dooley, 2020), which will constitute a quarter of the world total. Commonly, people entering the middle-class will pursue better quality of life, which creates immense additional purchasing power in the economy. The older generation in the middle-class apparently will follow the same pattern to improve their quality of life. Therefore, gerontechnology products such as the smart furniture introduced in this chapter will likely gain popularity among older adults especially in the middle-class.

5.4.3.3 Unique culture of filial piety

The success of a type of product depends largely on social and cultural acceptance, which provides psychological motivation for older adults and their caregivers to genuinely like using the products. The elderly-oriented smart furniture technology is no exception. In the Sinophone world (i.e., Chinese-speaking countries and regions), filial piety (Chinese: 孝, xiào) is a key virtue which refers to the respect, obedience, and love for one’s parents, grandparents, and even ancestors. Primarily promoted by Confucianism, this concept is arguably unique in the Chinese-speaking countries and regions with a history of more than 3000 years. The Chinese character of “xiào” is a vivid pictographic display of a child carrying his or her parent with long hair and a walking stick on the shoulder (Hsu, 2016). Figure 5-18 shows the evolution of this character from ancient to present.

Figure 5-18: The evolution of the Chinese character for “filial piety” from ancient to present

Under this cultural tradition, Chinese people have both the moral obligation and motivation to take care of their older parents in the best possible way. Filial piety, therefore, can be an excellent inherent advantage to promote elderly-oriented smart furniture or gerontechnological products in general in the Sinophone world.

5.4.3.4 Impact of “one-child policy”

The one-child policy was first introduced in 1979 by the Chinese government as a strategy to curb rapid population growth, mitigate poverty, and improving the well-being of children and women, but at the same time, the policy produced many unintended consequences such as gender imbalance and elderly care issues (Hesketh and Zhu, 1997). Figure 5-19 shows the author’s “Honorable Certificate for One-child Family”, which was issued by the government to families that committed to have only one child during the period when the policy was strictly implemented. Despite the comprehensive abolishment of the one-child policy in 2015 (officially replaced by two-children policy), births are still lagging. Meanwhile, whether to completely abolish family planning policy is still under fierce debate. Population aging is inevitable as economy and technology progress, but research showed that the nearly four-decade long one-child policy rapidly expedited the process (Zeng and Hesketh, 2016). As shown in Figure 5-20, a clear unnatural dent can be observed in China's population pyramids, which was primarily caused by the controversial "one-child policy".

Figure 5-19: "Honorable Certificate for One-Child Family" of the author

Figure 5-20: China's population pyramids in 2000, 2020, and 2050 (source: www.populationpyramid.net, licensed under CC BY 3.0 IGO, https://creativecommons.org/licenses/by/3.0/igo/)

In addition, the policy created other unintended consequences such as "4-2-1 family structure" and "lost-of-only-child family". Specifically, "4-2-1 family structure" refers to a family with four grandparents, two only-child parents, and one child. Due to the implementation of the "one-child policy" for decades, there were 1.58 million 4-2-1 families in 2015, and the number is expected to increase to 1.85 million in 2035 (Jiang and Sánchez-Barricarte, 2011). Given that the Chinese culture is significantly rooted in filial piety, this trend generates a substantial burden to the only-child generation parents as they need to take care of their parents and their children at the same time. On the other hand, lost-of-only-child family means a family whose only child has died but will not or cannot have another child due to age or other reasons. It was estimated that there were already 1.6 million lost-of-only-child families in China as of 2015 (Li, 2018). Apparently, significant measures shall be taken to relieve these two burdens. As a result, gerontechnology can play a crucial part in mitigating the impacts brought by the three-decade long "one-child policy", as it can increase the independence level of older adults.

5.4.3.5 Decent digital literacy among older adults

In general, according to China Internet Network Information Center, by the end of 2020, the number of Internet users over 60 years old in China reached 110.77 million, the vast majority of whom use mobile phones to access the Internet (China Internet Network Information Center, 2021). This means that more than 43% of Chinese older adults have digital literacy to some degree. Moreover, the results of this survey further suggested that majority of the survey participants (i.e., 60.9%) are interested in using smart furniture technology. Also, more than two thirds of the participants (i.e., 71.9%) expressed a positive projection regarding the market potential of smart furniture technology. All the evidence indicates that Chinese older adults are looking forward to using smart furniture technology to improve their quality of life.

5.4.3.6 State policy support

Zhang et al summarized four stages in the policy development of smart home for elderly care in China to date, including the seed stage (2008-2011), start-up stage (2012-2014), development stage (2015-2016), popularization stage (2017-present). In each stage, the state issued a variety of supporting policies to foster the development of elderly-oriented smart home technology, such as Development Plan of Social Elderly Care Service System (2011–2015), Comprehensive Reform Pilot of Elderly Care Service Industry (2013), Pilot Reform of Home-based Elderly Care Conducted by the Central Budget (2016), Several Opinions on Opening up the Elderly Care Service Market and Improving the Quality of Elder Care Services (2016), and the 13th Five-year Plan for Healthy Aging (2016–2020), just to name a few (Zhang et al., 2020). In the latest 14th Five-year Plan, the state elevated the active response to population aging to a national strategy (Xu, 2021). As many technological advancements in China have policy-driven characteristics, elderly-oriented smart home can potentially benefit greatly from these supporting policies.

5.4.3.7 Catalyst of the COVID-19 pandemic

The unprecedented COVID-19 pandemic has served as a catalyst for rapid digitalization and robotization of care solutions (Yang et al., 2020). Due to older adults' vulnerability to the pathogen, this process will especially benefit older adults in terms of making their life more independent and the health care system more resilient. The technologies developed REACH offer a wide range of digital solutions tailored to active aging and independent care of older adults in a variety of contexts along the care continuum: prevention, monitoring, functional training, healthy working life, nutrition, rehabilitation, remote care, and last but not least, independent living. This trend of digitalization in care applies not only to China, but also to the whole world.

5.4.4 Policy suggestions

In the beginning of this thesis, three major challenges imposed by population aging was listed: (1) the biological challenge which is to maintain good physical and mental ability in old age, (2) the social challenge which is to optimize policies related to aging, and (3) the cultural challenge which is to empower older adults to live with meaning and dignity (Sander et al., 2015). As a result, several policy suggestions from a technological point of view can be proposed based on the analysis above:

(1) The biological challenge:

- Further popularize the knowledge and public awareness on the importance of physical and cognitive activities to the whole aging population.
- Vigorously promote gerontechnology products that can increase the physical and mental activity level of older adults, thus increasing the quality of life of older adults.

(2) The social challenge:

- Revise the family planning policies according to the current demographic situation as soon as possible. The untimeliness of the two-child policy (evolved from the one-child policy) was elaborated in Section 5.4.3. Now is the time to adopt more flexible family planning policy. As of June 2021, China abandoned the two-child policy and moved to the "three-child policy" in a latest effort to combat its demographic crisis. However, many experts argue that merely this policy revision is unlikely to solve the deep-rooted problem (Tatum, 2021). Other supporting measures such as tax cuts and subsidies shall be implemented in concert to effectively alleviate the population challenges.
- Spend more on research and development in aging and gerontechnology topics (e.g., elderly-oriented smart furniture) and promote the "silver economy" (i.e., an economy that also works for older members of society).
- Provide financial incentives (i.e., tax cuts or subsidies) for the elderly care industry including hospitals, retirement homes, and gerontechnology companies.
- Introduce overseas migrant workers with caution. The social impact brought by migrant workers has been observed in neighboring societies such as Hong Kong SAR (Constable, 2009). Therefore, it can start with accepting migrant workers from populous neighboring countries with close cultures (e.g., Vietnam, Laos, Myanmar, Cambodia, etc.) to minimize potential social impact, then gradually expand to other countries as well.
- Provide expense coverage of the gerontechnology products (e.g., Ambient Rehabilitation Kit) via the national healthcare insurance system (i.e., China Healthcare Security).
- Reform higher education regarding admission, curricula, and organization into a more flexible and integrated system that can cultivate more interdisciplinary talents in order to adapt to the forthcoming challenges in aging society. Moreover, emerging technologies should be introduced in the curricula of all faculties, not just in STEM

majors (i.e., science, technology, engineering, and mathematics), in order to improve students' ability to adapt to the rapid development in technology (Ma and Siau, 2019). It is particularly true in design education which needs to teach not only traditional design skills but also knowledge from other subjects such as engineering and social science in order to brace for future social challenges (Lu et al., 2018).

(3) The cultural challenge

- Eliminate the stereotypical image of frailty, slowness, and inactivity against older adults and promote active aging lifestyle.
- Promote the idea of "never too old to be cool" to society and promote the use of gerontechnology products (e.g., smart furniture, serious gaming devices, wearables) for health benefits.

5.4.5 Project action plan

From the results of the survey, it can be summarized that the majority of surveyed Chinese older adults, especially those who are younger than 80 years old (the "young old" and "middle old"), already have good capability of using at least one smart personal devices and smart home devices. Furthermore, the majority of the survey participants believed that there will be great potential for the smart furniture market of China in the near future. It can be inferred that a few years from now, the vast majority of Chinese older adults will become potential customers of smart furniture products.

Admittedly, a great concept can never be truly great if it merely stays on paper. As suggested by the survey results, the market potential for elderly-oriented smart furniture in China is substantial. As expected, two large Chinese furniture companies (one focuses on commercial furniture, the other on medical furniture) currently have already showed strong interest in cooperating with the REACH start-up with regard to introducing the Ambient Rehabilitation Kit. Furthermore, the commercial furniture company already agree to initiate a consultancy project with the REACH start-up company to investigate the feasibility on the Ambient Rehabilitation Kit in the context of China. The project officially kicks off in January, 2022. Follow-up projects are expected to be carried out in the Chinese context within the next several years.

As a result, a three-year action plan for conducting a R&D project for implementing smart furniture technology in the Chinese market in collaboration with the local furniture company is proposed, following the Deming Cycle (see Figure 5-21). Currently, the company has already agreed to execute this project. The project will be divided into two phases: Phase 1 – Strategic Consultation (1-12 months) and Phase 2 – System Implementation (13-36 months). The tasks and schedule of the project are detailed in Figure 5-20. After the end of Phase 1, a 1:1 showroom will be built up in Guangdong Province of China to demonstrate the PI^2Us and other relevant technologies to the older Chinese audience. This follow-up project will be one of the first systematic R&D projects to implement elderly-oriented smart furniture solution (i.e., Ambient Rehabilitation Kit) in the mainland Chinese market. The project results will be revealed in future publications.

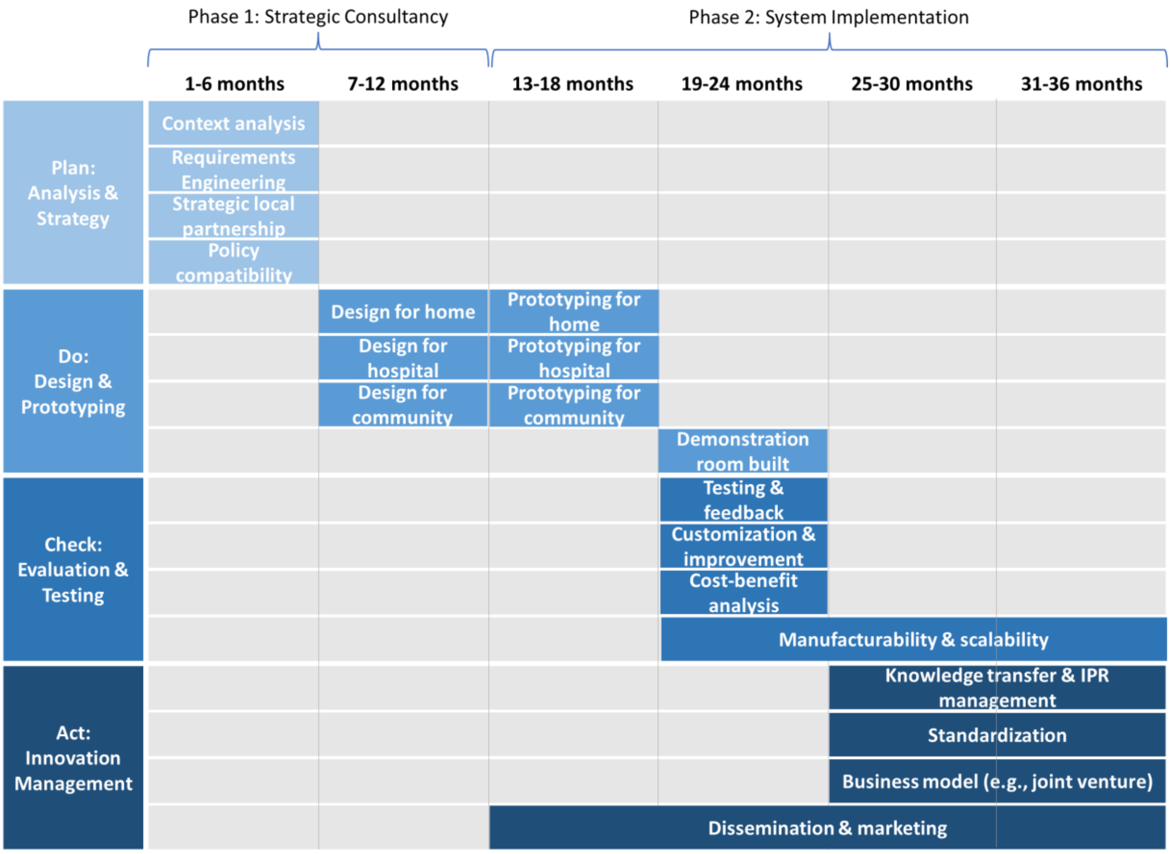

Figure 5-21: Three-year action plan for a two-phase R&D project to implement smart furniture technology in China

Admittedly, plenty work remains to be done for the comprehensive implementation of elderly-oriented smart home in China. Zhang et al. summarized several main hurdles facing the development of smart home in China, including insufficient demand caused by lack of public awareness, imbalanced development due to a lack of regulation, and wasted public and private resources due to unplanned investment (Zhang et al., 2020). However, the findings and analyses of this chapter shows a clear path to overcome these challenges, which answers RQ4 (i.e., how can the proposed system be introduced to markets outside Europe?). In conclusion, there are sufficient reasons to believe that China's elderly-oriented smart furniture and smart home in general has a prosperous future, which will in turn provide valuable lessons of implementing elderly-oriented smart home technology for the rest of the world, especially the Global South.

6 From micro to macro: A framework for developing future smart cities based on state-of-the-art building technologies (Plan)[11]

"It always seems impossible until it's done."

Nelson Mandela[12]

The first cycle of development of the Ambient Rehabilitation Kit was elaborated above. However, only implementing elderly-oriented smart furniture on the micro level will not be sufficient to mitigate the impact of the global population aging crisis. A more comprehensive framework for developing future city on a larger scale using advanced building technologies needs to be explored in order to better fulfilling the ever-changing needs of the users and society. Therefore, in the beginning of the second development cycle, the doctoral research attempts to integrate the Ambient Rehabilitation Kit into a bigger context, depicting a visionary outlook of what the future city could look like. This chapter also lays the foundation for the author's future research endeavors.

A city is a sophisticated organism which is constantly changing throughout its lifecycle, as a result of economic shifts, demographic change, and environmental pressures. Nowadays, megacities in China are facing unprecedented issues such as overpopulation, population aging, land shortage, ghost cities, and environmental pressures during the process of uncontrollable urban sprawl (Chen et al., 2016; Li et al., 2019). Meanwhile, a considerable number of new developments claim themselves in the title of "vertical city", yet very few represent the essence of a city. The definition of vertical city cannot be solely judged by its height, usage, or investment return, but has to demonstrate the capability of adaption in response to urban transformation. This chapter aims to explore a novel framework of vertical city, or in other words, Dynamic Vertical Urbanism, featuring constant vertical urban transformation through applying the state-of-the-art construction technologies preliminarily in the context of megacities in China. Meanwhile, this vertical city approach has the ability to integrate city's basic elements such as paths, edges, districts, and landmarks (Lynch,

[11] This chapter is partially based on the research article entitled "Towards Dynamic Vertical Urbanism: A novel conceptual approach to develop vertical city using construction robotics, open building principles, and prefabricated modular construction" (Hu et al., 2020b) published in International Journal of Industrialized Construction, Volume 1, Issue 1, and has been reproduced here with the permission of the publisher, see appendices. The authors retain the copyright of this publication according to the publisher (see Appendix IV: Letters/statements of reuse permission from publishers). Authors' contributions: R. Hu (correspondence, conceptualization, literature review, co-design, modeling, visualization, writing-original draft preparation, writing-review and editing), W. Pan (co-design, modeling), T. Bock (conceptualization, supervision).

[12] Nelson Mandela (1918-2013): Anti-apartheid revolutionary and Former President of South Africa.

1960). More importantly, it can change its size, form and function with the help of construction automation technologies and Open Building principles. It can also responsively evolve in accordance with social, economic, and environmental shifts in a self-sufficient manner, meanwhile avoiding homogenization with surrounding buildings. Eventually, the complex will perform as a series of interconnected components which act together to form a living organism that performs a variety of functions and purposes. (Hu et al., 2020b)

6.1 Background and literature review

In this section, the current situation and research gap of vertical city are concisely described. Furthermore, building complexes in different cities with various destinies are demonstrated, which inspire the Dynamic Vertical Urbanism approach. In addition, urban design theories and building technologies that are crucial for the implementation of this approach will be introduced.

6.1.1 "Vertical city": the research gap

Today, the concept of "vertical city", a type of terminology that has never been strictly articulated, is becoming more and more popular (Lin and Gamez, 2018). Many cities around the globe are enthusiastically adopting tall buildings in the name of vertical city as one of the main building typologies (Al-Kodmany, 2018). Multiple factors fostered the rise of the vertical city concepts and practice. There are several key factors that catalyzed the generation of vertical city concepts: (1) rapid population growth especially in urban areas, (2) deteriorated ecological conditions in cities caused by overpopulation and urban sprawl, (3) the urgent need for sustainable development, (4) urban residents' desire to lead a comfortable lifestyle, (5) severe land shortage in large cities (Akristiniy and Boriskina, 2018), and (6) the urgent need for preserving arable land to ensure food security (A. Chen et al., 2019; Kong, 2014). Accumulated building technologies make it possible to build large urban complexes in a vertical manner, and a large number of new developments in East Asia, the Middle East, Europe, and Americas portray themselves as "vertical cities" (Howarth, 2013; Robinson, 2016; Rosenfield, 2012). However, few of them address one key essence of a city, which is the ability to continuously grow and transform in terms of forms and functions.

6.1.2 Learning from St. Louis, Tokyo, Cairo, and Chicago

Oftentimes a building will face an unpleasant destiny when it reaches the end of its lifecycle, which is demolition. Designed by renowned architect Minoru Yamasaki, Pruitt-Igoe, St. Louis is arguably the most infamous failure of American social housing projects. Largely due to issues such as insufficient building quality, homogeneous design of each building, lack of functional flexibility, poor maintenance, occupancy rate decline, poverty, crime, and racial segregation, the over-scale complex of 33 buildings were demolished with explosives in 1972, which later became a symbolic event of unreasonable planning and waste of construction resources (Samaratunga and O'Hare, 2013). Presumably, Pruitt-Igoe might have a completely different fate if all these above-mentioned issues were properly addressed (see Figure 6-1).

Figure 6-1: Aerial views of the Pruitt-Igoe complex before and after the explosion. Left: United States Geological Survey (public domain); right: U.S. Department of Housing and Urban Development (public domain)

Contrary to Pruitt-Igoe, however, a silver lining can be found in the influential Metabolist movement in Japan. Let us take a glance at two notable buildings in Tokyo created during the Metabolism movement. The first one is the Nakagin Capsule Tower which was designed by Kisho Kurokawa and completed in 1972 (see Figure 6-2). As the world's first capsule architecture put into use, it is considered revolutionary for its futuristic appearance, modularized design, and factory-produced living units. After Japan's economic bubble burst in early 1990's, the building's fate began to turn grim. Due to lack of funds, the interior of the building fell into disrepair (Ouroussoff, 2009). Finally, it was reported in 2007 that the association of tenants at the Nakagin Capsule Tower voted to demolish this historic landmark because of the use of asbestos in the capsules, the concerns of its ability to withstand earthquakes, and more importantly, its inefficient use of land (Lin, 2011; Ouroussoff, 2009). Another example worth noting is the Fuji TV Building designed by Kenzo Tange (see Figure 6-3). Besides the magnificent spherical observation platform, one of the most eye-catching highlights of the building is three pairs of enclosed pedestrian sky bridges connecting the media and office towers, which create a considerable amount of flexibility and mobility for its occupants (Architectuul, n.d.). Being a large futuristic multifunctional complex, however, the main function of this tower as a whole was mostly fixed since its erection in 1997, which is the headquarters of Fuji Television Network.

By observing these two signature projects of the Metabolist movement in Tokyo, it is obvious that they opened a whole new door in the field of architectural design for their industrialized modularity and interconnectivity. However, they both are far from been considered as "Vertical Cities" due to abovementioned reasons. Admittedly, they broke fresh ground in the history of architecture, but their functions and volumes are still not able to evolve in accordance with social, economic, and environmental changes.

Figure 6-2: Nakagin Capsule Tower in Tokyo, Japan. Photo By Jordy Meow (unchanged and licensed under CC BY-SA 3.0, https://creativecommons.org/licenses/by-sa/3.0/)

Figure 6-3: Fuji TV Building in Tokyo, Japan. Photo by Kakidai (unchanged and licensed under CC BY-SA 4.0, https://creativecommons.org/licenses/by-sa/4.0/)

To answer the question that Metabolism did not clearly answered, we can find some inspiration from Cairo's urban slums. Cairo, the capital city of Egypt, is arguably the largest metropolis in Africa, and one of the largest in the world. Today, around two-thirds of Greater Cairo Region's 20 million residents live in urban informal settlements (see Figure 6-4). Even though various issues such as overpopulation, high unemployment rate, land shortage, poor living conditions, inadequate infrastructures, and environmental challenges exist in these informal settlements, they still manage to achieve self-sufficiency and maintain a strong community through their seemingly chaotic, but flexible structural system, which can be continuously extended vertically (and in some cases even horizontally) (Follini et al., 2017; Hu et al., 2017).

Figure 6-4: An aerial view of Cairo's informal urban settlements. Photo by Silar (unchanged and licensed under CC BY-SA 3.0, https://creativecommons.org/licenses/by-sa/3.0/)

In the research project A^{2}L-Mobilius (funded by the Germany Ministry for Education and Research, Grant Number: GERF-IB-033 Almobilius_01DH14003), inspired by Cairo's informal communities, researchers developed an affordable and adaptable building system (A^{2}BS) to help to gradually transform the informal settlements. As shown in Figure 6-5, the system is based on the principle of Open Building concepts, which consist of three sub-systems that can be easily prefabricated by local residents: the modular structural sub-system, the building envelope sub-system, and the service infill sub-system. The structure itself can be extended vertically and horizontally with newly built, structural elements in order to achieve maximum flexibility and to allow the building to evolve over time (Hu et al., 2018).

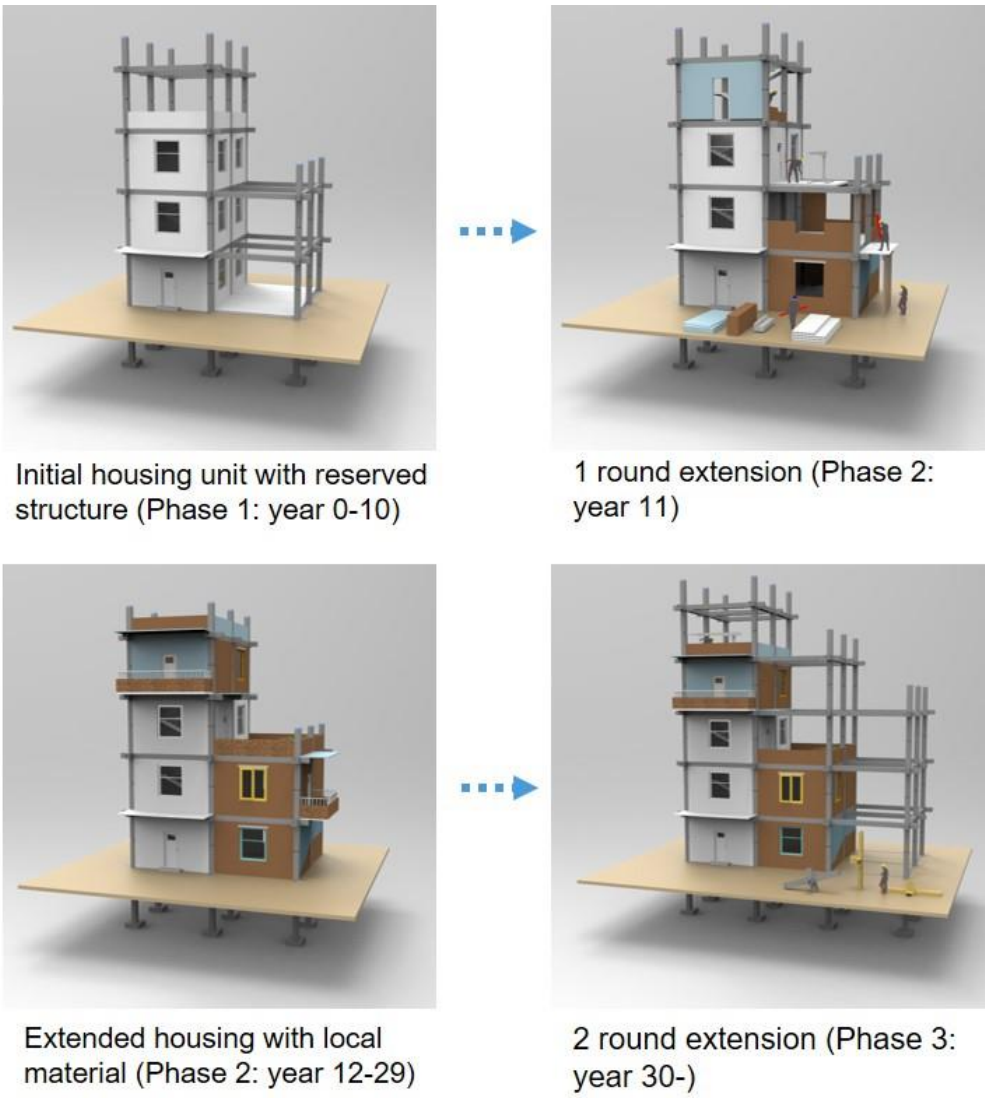

Figure 6-5: An evolutionary development scenario of A^{2}BS Building System

A similar approach also can be observed in the design and construction process of large modern commercial buildings. For instance, Blue Cross Blue Shield Tower in Chicago, Illinois, is a 57-story, two-phased, vertically expanded office tower. The building's 33-story first phase was completed in 1997, and more than 10 years later in 2010, phase two was completed, adding 24 stories on top of the original, fully occupied building. During the expansion process, occupation in the lower original building remains normal and uninterrupted (Goettsch Partners, n.d.). This example shows that through the innovative concept of vertical expansion, a building can successfully plan for a long-term growth without relocation, thus providing an excellent reference for the future expansion of vertical city (see Figure 6-6).

Figure 6-6: Blue Cross Blue Shield Tower in Chicago during expansion. Photo by Photogal (unchanged and licensed under CC BY-SA 3.0, https://creativecommons.org/licenses/by-sa/3.0/)

6.1.3 Review of theories and technologies to be applied in the novel vertical city framework

In order to achieve perpetual vertical urban transformation, there are several interconnected concepts and technologies which will serve as the core pillars of Dynamic Vertical Urbanism (see Figure 6-7). These concepts and technologies will be analyzed in the following sections.

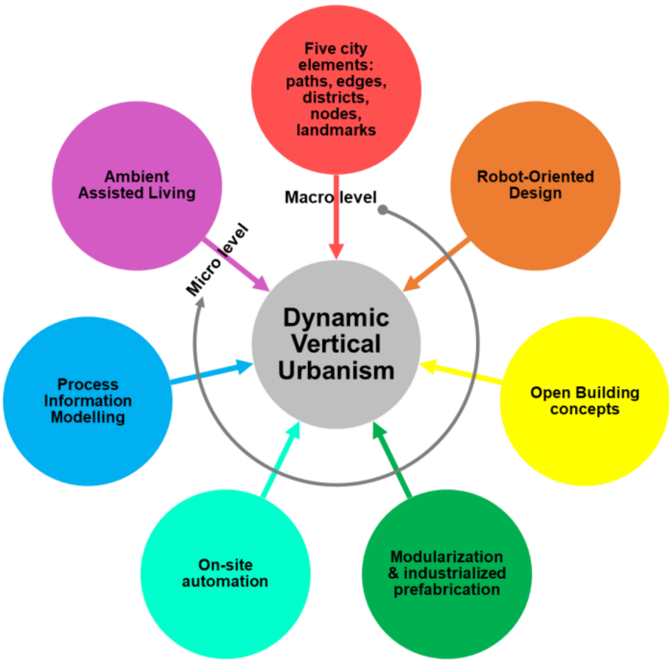

Figure 6-7: Seven pillars in the novel vertical city framework

6.1.3.1 Five city elements

In the book The Image of the City (1960), Lynch concluded that people formed mental maps of the surrounding urban area through five tangible elements: paths, edges, districts, nodes, and landmarks (Lynch, 1960). Accordingly, in order to achieve the authenticity of a vertical city, these five elements must be interpreted and reflected in the design process. Specifically, the novel vertical city has vertical and horizontal circulation systems as its paths, a flexible building envelope as its edges, variable mixed-use functional blocks as its districts, sky bridges and roof gardens as its nodes, and the complex itself as a landmark.

6.1.3.2 Robot-Oriented Design

For many years, there has been a need of redesign of various construction tasks that are simple, repetitive and dangerous using ergonomic principles and automation technologies (Skibniewski and Zavadskas, 2013). Therefore, Bock first initiated the concept of Robot-Oriented Design (ROD) in 1988, which emphasizes the idea that before the final on-site construction process, all parameters shall have been already considered at the earlier design and production stages. In order to establish determined conditions for robotic on-site operations, the elements of building subsystems (e.g., building structure, component, assembly method, and equipment selection, etc.) need to be well defined geometrically and physically in accordance with robotics and automation (Bock, 1990).

6.1.3.3 Open Building concepts

Open Building is a cross-disciplinary approach to the design of buildings that takes in account the possible need to change or adapt the building during its lifecycle, in accordance with social, economic, and technological changes. Open Building concepts gradually emerged in response to evolving social, political and commercial forces, to prevailing conditions and trends in residential construction, manufacturing and many other factors that demand more efficient and susceptive practices. The building is designed on different levels: support structure, infill system, fit-out and appliances (Cuperus, 2001; Kendall and Teicher, 2000). Researchers have developed a number of Open Building systems on various levels (Chien and Wang, 2014; Cuperus, 2001; Kadowaki and Fukao, 2001). All these levels have been updated and reinterpreted to utilize the benefits of state-of–the–art industrial production, emerging information technologies, improved logistics and changing social values and market structures. Apparently, buildings following Open Building principles will by no means become obsolete but will perpetually evolve in accordance with occupants' demands. Since its initiation, Open Building principles have been widely adopted by architects around the world in numerous projects, including the renowned NEXT21 in Japan and Molenvliet Project in Netherlands (Habraken, 2003).

6.1.3.4 Modularization and industrialized prefabrication

Modularization and industrialized prefabrication play a significant role during the lifecycle of the novel vertical city approach. Usually several levels are defined in building prefabrication: lower-level components made of raw materials and parts (e.g., ceramic, brickwork, concrete, wood, steel, glass, polymers, etc.), mid-level building components (i.e., building subsystem manufacturing, such as kitchen modules, bathroom units, assistance modules, etc.), and high-level complete, prefabricated buildings (Bock and Linner, 2015; Linner and Bock, 2012). In the novel vertical city approach, all main parts and components of the building will be prefabricated in factory while complying with Open Building concepts, in order to achieve flexibility and sustainability throughout the lifecycle of the vertical city.

6.1.3.5 On-site automation

Since the late 1980s, Japanese contractors began to realize that payoffs of single-task robots were limited unless more of the construction process could be automated and integrated. Therefore, they began to explore the application of manufacturing principles to construction (Maeda, 1994). There are four fundamental elements in an on-site automation system: (1) an on-site factory protected by an all-weather enclosure, (2) an automated jacking system, (3) an automated material conveying system, and (4) a centralized information control system. Most of the on-site construction factories use a just-in-time material delivery system, bar-coded parts or components, and a computerized information management system to improve the efficiency and quality of the construction process. Other tasks such as welding, painting, and concrete finishing can be further carried out by single-task construction robots. In addition, the on-site construction factory system can also be applied to the deconstruction process.

For example, Big Canopy, designed by Obayashi Corporation in 1995, was the first automated construction system applied to the construction of precast concrete structures. The Big Canopy itself is supported by at least four independent massive columns around the building, which allow more flexibility than other previous systems. In addition, the system has a synchronously self-climbing temporary roof, climbing devices, and overhead/jib cranes, all of which are supported by the massive columns. Once the floor is erected, the canopy is jacked up one story at a time and always left a two-story space in between the canopy and the on-site factory floor. Furthermore, the system has a parallel material delivery system which consists of overhead cranes and material delivery lifts (see Figure 6-8a) (Bock and Linner, 2016b; Taylor et al., 2003).

The HAT Down method, developed by Takenaka Corporation, is a closed sky factory supported by the building itself (i.e., moving downwards). The HAT Down system, which can be considered as a reversed on-site construction factory, consists of a series of integrated subsystems: a sky factory roof structure; a descending system; a horizontal delivery system; lowering shafts; a material handling, sorting, and processing yard; a real-time monitoring and management system; and templates for cutting. In addition, a deconstruction site requires some novel types of end-effectors, such as a material sorting device for recycling, water-cutting, and laser-cutting (see Figure 6-8b) (Bock and Linner, 2016b).

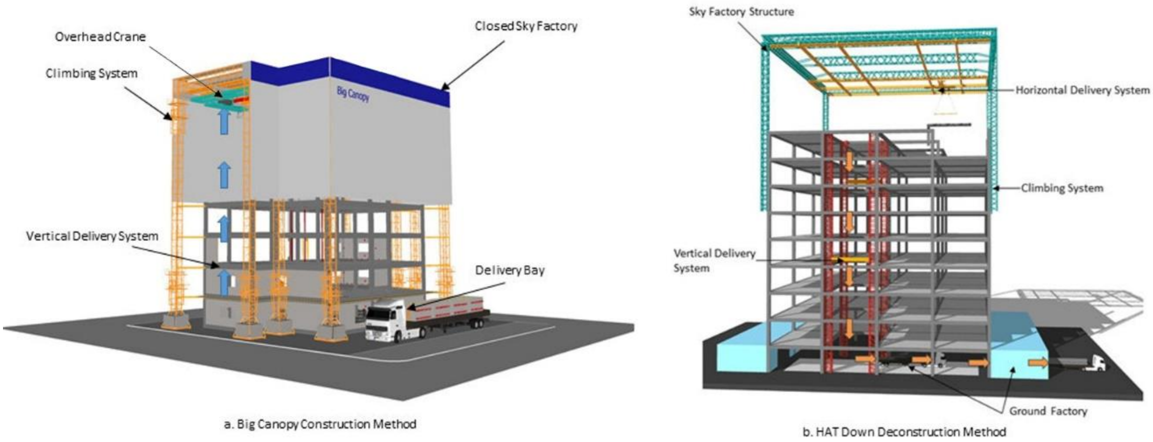

Figure 6-8: On-site automation sites (left: Big Canopy Construction Method by Obayashi Corporation; right: HAT Down Deconstruction Method by Takenaka Corporation)

6.1.3.6 Building Information Modeling

It is widely known that project management, which is the subject of coordinating different projects and keeping them on track within limited time, cost and resource, helps to create better plans, schedules, and profit (Hajdu, 1997). To carry out an ambitious concept, an integrated project management framework that offers seamless, real-time data accumulation, processing, and distribution is required. In addition, the proposed management framework will cover design, manufacturing, logistics, on-site assembly, and lifecycle management phases of the tall building construction project. In this case, in order to manage a large amount of heterogeneous data from the physical and digital surrounding, only understanding the real word condition through knowledge-based and/or object-oriented technologies such as traditional Building Information Modeling (BIM) application is insufficient. In addition, when implementing automation and robotic construction technology in the construction process, a know-how based, interactive, proactive and responsive version of BIM is required (Eastman et al., 2008).

6.1.3.7 Ambient assisted living

As the global population keeps aging rapidly, the novel interdisciplinary research field of ambient assisted living (AAL) addresses the needs of older adults. It aims at developing ambient-integrated gerontechnology products to assist older adults to live independently in their familiar living environment as long as possible. The first ideas of AAL occurred in the 1970s, which combined technologies from various fields such as sensing, mechatronics, robotics, medicine, and smart home (Bock et al., 2019). Today, AAL has become a lively research topic with a promising future, attracting more and more researchers, engineers, educators, investors, as well as policy makers to make contributions to it. It is also foreseeable that AAL will play a crucial role on the micro level of future vertical cities.

6.2 Proposal of a framework for developing future vertical city

Based on the analyses in the previous sections, a comprehensive approach is proposed to develop the vertical city with the concept of Dynamic Vertical Urbanism. First of all, the proposed type of building complex is not supposed to be constructed in the congested urban centers, but in suburban areas near congested metropolises, serving as a self-sufficient satellite-type “vertical city” to support the most populated urban areas through rapid transit. Specifically, the novel vertical city complex has vertical and horizontal circulation systems as its paths, a flexible building envelope as its edges, variable mixed-use functional blocks as its districts, sky bridges and roof gardens as its nodes, and the complex itself as a landmark. Furthermore, each tower is overstructured to enable continuous expansion to a certain extend. It is worth mentioning that the proposed design complies with the design principles of sustainable skyscrapers concluded by Wood (Wood, 2015), including variation with height, new programs, communal spaces, envelope opacity, sky bridges and integrated vegetation. In addition, the research also closely follows the Roadmap on the Future Research Needs of Tall Buildings formulated by Council on Tall Buildings and Urban Habitat (CTBUH) (Oldfield et al., 2014). The detailed design concept is described and explained as follows.

6.2.1 Design overview

The proposed design demonstrates a type of floor plan that is commonly seen in China’s construction industry (see Figure 6-9). There are four wings allocated around the central core structure. In order to maintain efficiency, each wing consists of maximum ten units (whether they are residential or office), which can be flexibly used for residential, commercial, office, and public purposes (e.g., school, hospital, police station, infrastructure, etc.) depending on the requirements of the stakeholders (see Figure 6-10). There are dedicated void spaces reserved on either side of the wing where the massive column structures for the self-climbing systems of the on-site factories are located (see Figure 6-11).

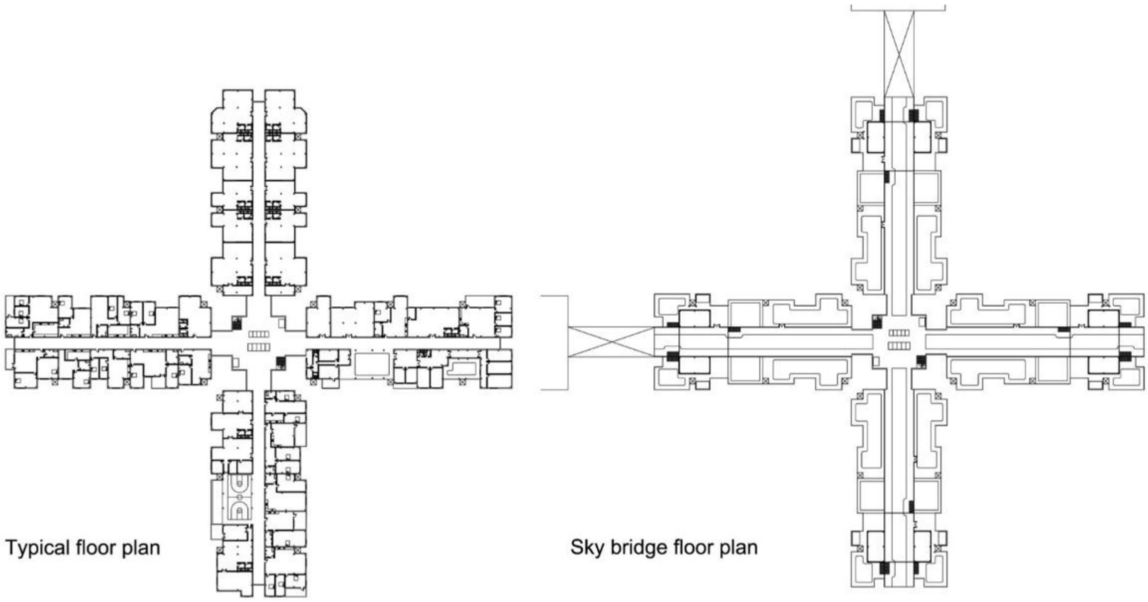

Figure 6-9: Typical floor plans in the Dynamic Vertical Urbanism complex

Figure 6-10: An exemplary section of the Dynamic Vertical Urbanism complex

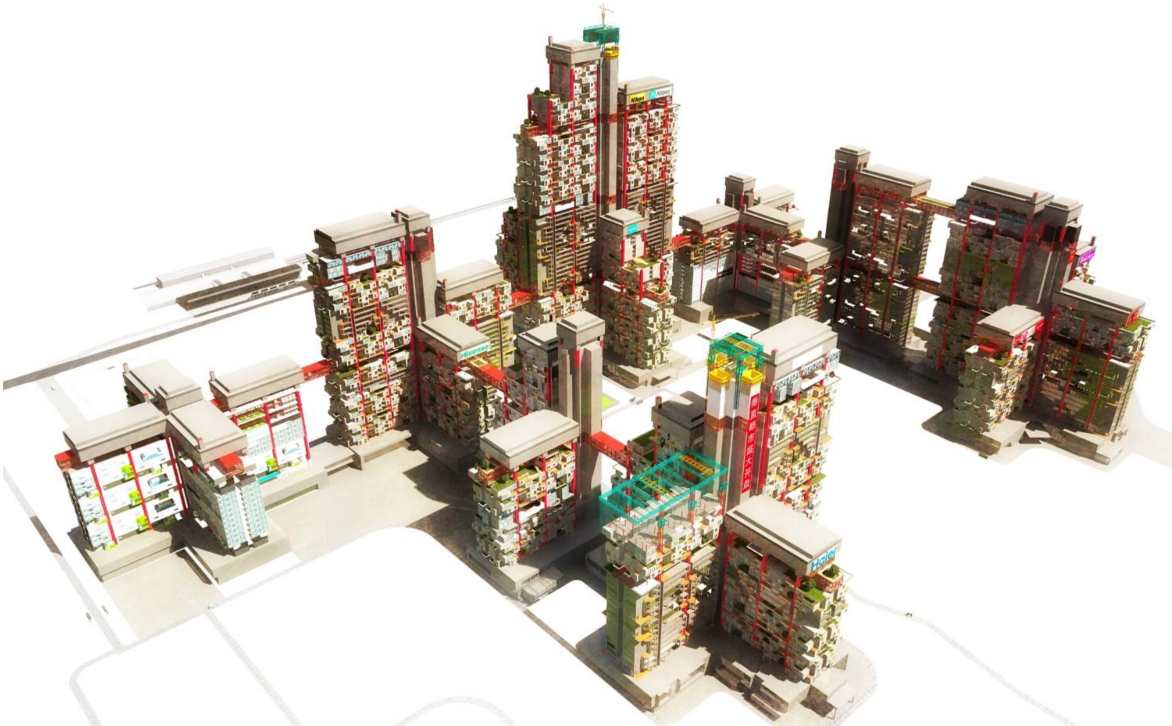

Figure 6-11: Aerial view of the proposed complex following Dynamic Vertical Urbanism principles

6.2.2 On-site construction factory

In order to reduce the effects of the harsh surroundings on the robot performance as well as to provide a clean, quiet and unobtrusive jobsite environment to enable early and continuous occupation of the residents, it is critical to adopt automated construction factories (Cousineau and Miura, 1998). On-site construction factories (OCF), which consists of the sky construction factory (SCF) and the ground construction factory (GCF), play a crucial role in the development of Dynamic Vertical Urbanism (see Figure 6-12). With the help of the industrialized building design and the utilization of automation technology, the proposed concept attempts to transform conventional construction sites into on-site assembly environments. Inspired by the self-climbing crane and special crane application in the ship building industry, the on-site construction factory is designed to assemble the building with minimal human intervention. Supported by a GCF on the ground floor, which is mainly responsible for shipping/receiving, restoration, and assembly, there is a perpetual SCF responsible for the erection process on top of each tower. Each one of them can independently function, extend and retract, and they operate under a specific protocol that improves construction efficiency and safety (see Figure 6-13) (Kim et al., 2009).

When the section of the wing is completed, the SCF will be retracted, hoisting equipment will be dissembled, and the vacant frame structure will be lowered into position and will function as the roof of the building. Apart from the central SCF, each wing SCF is equipped with two automated gantry cranes. The gantry crane will cover the entire construction shop floor of the building. The central SCF benefits from an automated gantry crane and a jib crane. The jib crane is responsible for vertical material transportation for the central SCF and carrying out the initial construction of the other four SCFs.

The hoist module functions as the end effector of the automated gantry crane, which is equipped with the smart crane hoist system to keep delivery balanced as well as to provide vertical and horizontal transportation of the building components. The hoist module is also equipped with a sensor-controlled configuration system to help identify the location of the panel and following pre-programmed assembly sequences. The motion displacement of the robot can be manually operated, and in case of emergency, it will switch to an autopilot control system. The robot control system is connected with the main site control facilities and the project management information system (Pan, 2013). Once the building components with the auto-alignment feature reach the correct assembly location, the connections will be fastened by means of the dry connection method. Bolting and on-site assembly activities will be implemented by single-task construction robots to increase assembly speed.

The vertical material transportation platform is controlled by a lifting planning system that generates a lifting plan based on data such as floor heights, acceleration distance, reduction time, number of stops, construction material input speed, lifting cycle, material transfer speed and waiting time. The data required can be collected from the radio frequency identification tag (RFID) and ZigBee sensors which are located on the building structure or embedded in the building materials (Murray et al., 2003). The base of each tower will function as a material loading, sorting and pick-up station during the construction, expansion and maintenance process. A programmable logic controller (PLC) is used for controlling the picking system. In the off-site factory, each building component is allocated with a RFID tag. When they arrive on site, the tag will be scanned and the information will show the exact assembly sequence and assembly position of each component. Then the components will be placed onto the picking station in the correct order, ready for lifting and assembly (Neelamkavil, 2009).

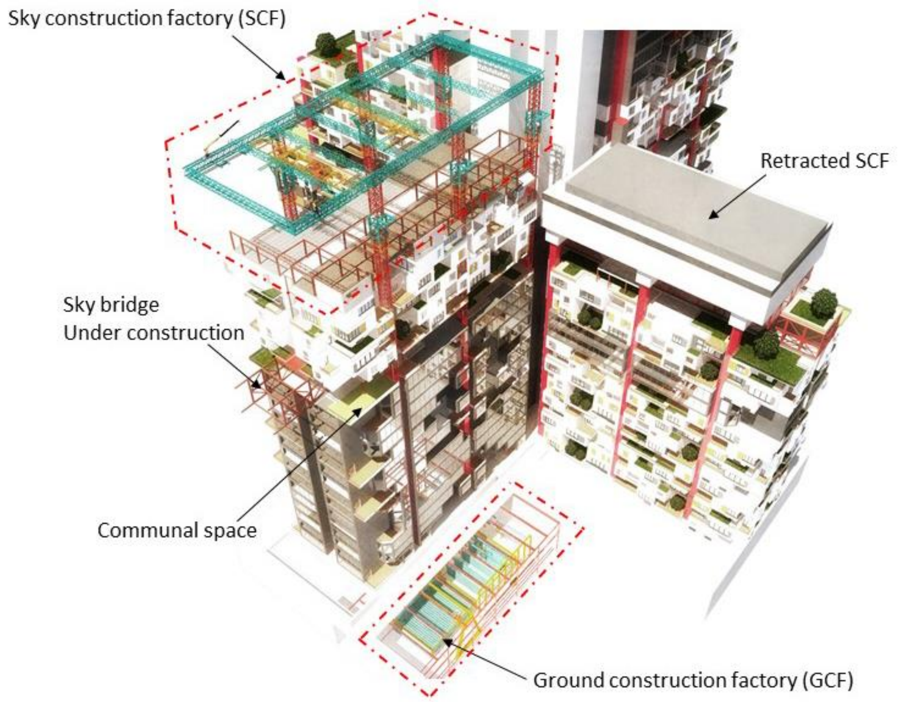

Figure 6-12: Sky construction factory and ground construction factory

Figure 6-13: Exterior and interior views of the sky construction factory

6.2.3 Sky bridges

The sky bridge, which serves as the main horizontal paths or streets connecting different towers, as well as a community gathering space for multiple activities (Wood, 2003), will be assembled by the correspondence SCF that depends on the direction where the sky bridge will extend. The SCF will be extended by using a smaller integrated crane on the upper deck of the mainframe structure. Then, the automated gantry crane will construct the sky bridge. Eventually, the sky bridge shall be interconnected from either side by using integrated retractable assembly systems (see Figure 6-14). Various means of mobility technology such as travellators and rope-free elevators (Morris, 2017) can be utilized within the sky bridges and central building cores to catapult the efficiency of internal transportation.

Figure 6-14: Exterior and interior views of the sky bridge

6.2.4 Open building approach

Following the Open Building concepts, the building system of Dynamic Vertical Urbanism can be divided into four subsystems: structures, non-load-bearing components, services and construction. In general, structural systems include a series of steel beams and columns that are interconnected and provide a flexible box-shaped support system. The prefabricated concrete double ribbed floor panel also classifies as part of the structural system. Non-load-bearing component systems include precast concrete floor panels and sandwich wall panels. Services system consists of interior fixtures, electrical, plumbing fixtures, and heating, ventilation and air conditioning (HVAC) of the building. Each part can be easily assembled or disassembles so that the building system is able to be upgraded or modified according to the specific demand of each end-user. Furthermore, various AAL modules (see Section 2.4) can be easily deployed in the modular living units according to each end-user's needs (see Figure 6-15).

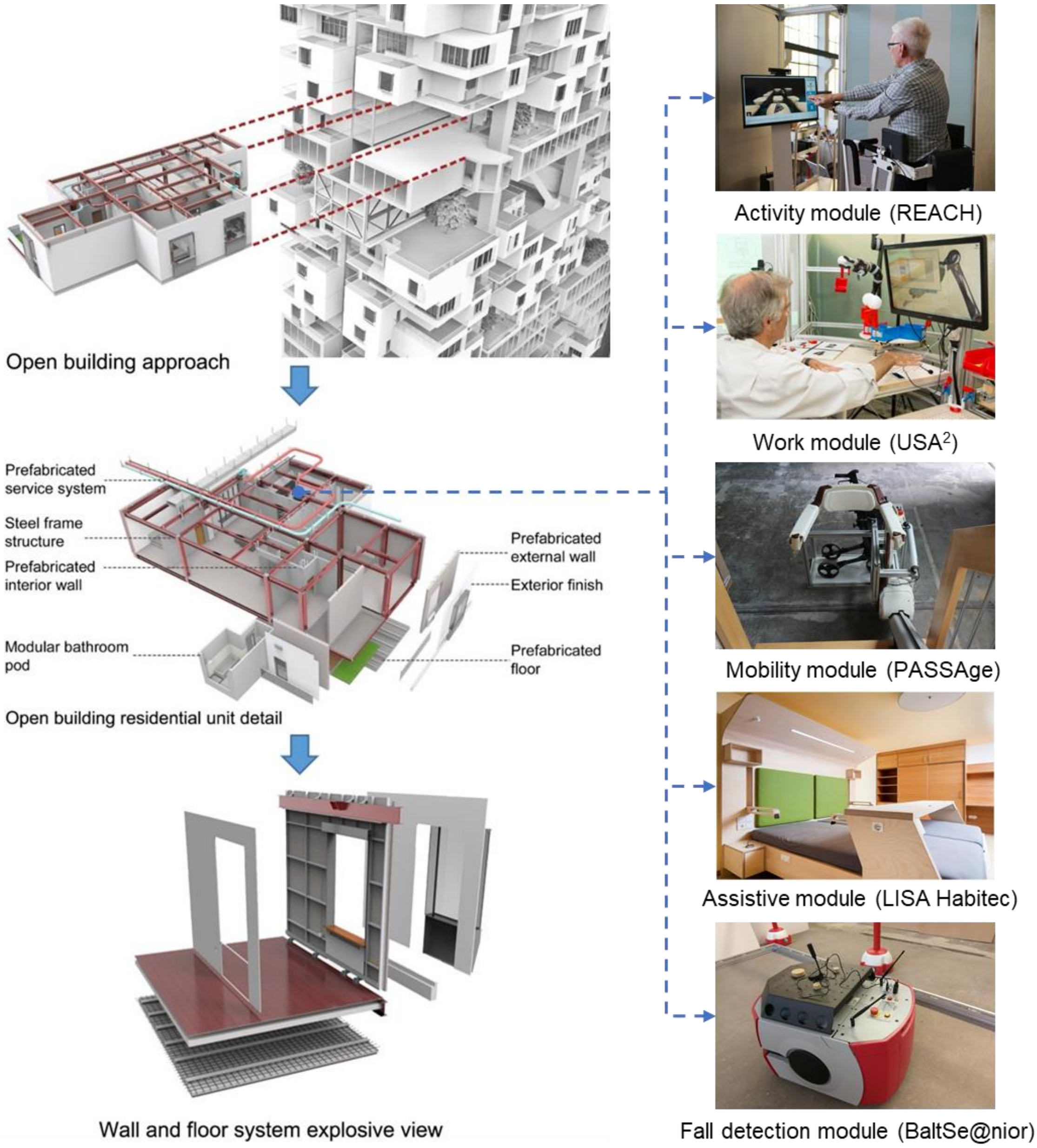

Figure 6-15: Open Building system in Dynamic Vertical Urbanism integrating AAL various systems (source: USA²- Schlegelmilch; LISA Habitec - MM Design)

6.2.5 Integration of Ambient Rehabilitation Kit

As introduced in detail in the previous chapters, the Ambient Rehabilitation Kit can be a powerful tool to mitigate the impact of population aging. It is also an important component in the framework of Dynamic Vertical Urbanism on the micro level. Because it is a highly modularized and customizable system, it can be easily customized and integrated into different according to the resident's needs (elaborated in Chapter 3). Figure 6-16 visualizes the integration of the modular Ambient Rehabilitation Kit (e.g., SilverArc, MiniArc, SilverBed, iStander, ActivLife) in the residential module, assisting the ADLs (e.g., resting, training, gaming, cooking, etc.) of aging residents and beyond.

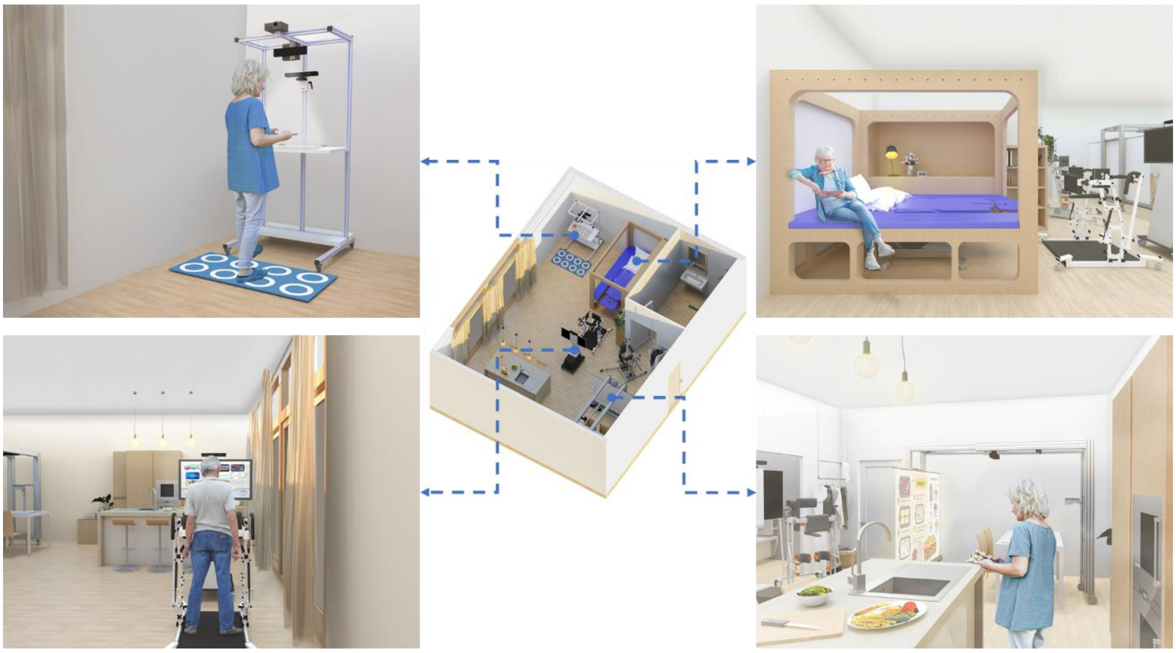

Figure 6-16: Ambient Rehabilitation Kit integrated in the residential unit wherever needed (image: M. Schmailzl and R. Hu)

6.2.6 Process Information Modeling platform

In order to establish the central "nervous system" of the proposed vertical city concept, the concept of Process Information Modeling (PIM) is introduced based on the accumulated progress in BIM. In general, PIM aims to provide a collaborative way of planning, designing, producing, assembling and managing throughout the entire project life cycle. The main objective of PIM is to adopt the current BIM technology and supplement it with a process-oriented database platform, allowing for smooth data transfer, as well as promoting seamless and constant data sharing among all stakeholders. Digital documentation, simulation and real-time data are progressively produced to support the decision-making process. The PIM platform will collect real-time information from dedicated data clusters, then store, categorize, process, and distribute the most relevant information to the right stakeholder at the right time. In the same manner as the proposed Dynamic Vertical Urbanism concept, at the time of writing this thesis, PIM is under conceptual development. Based on the current research progress of the PIM technology, Figure 6-17 shows the preliminary system architecture of the proposed PIM platform for developing the entire life cycle of the Dynamic Vertical Urbanism complex (Pan et al., 2018).

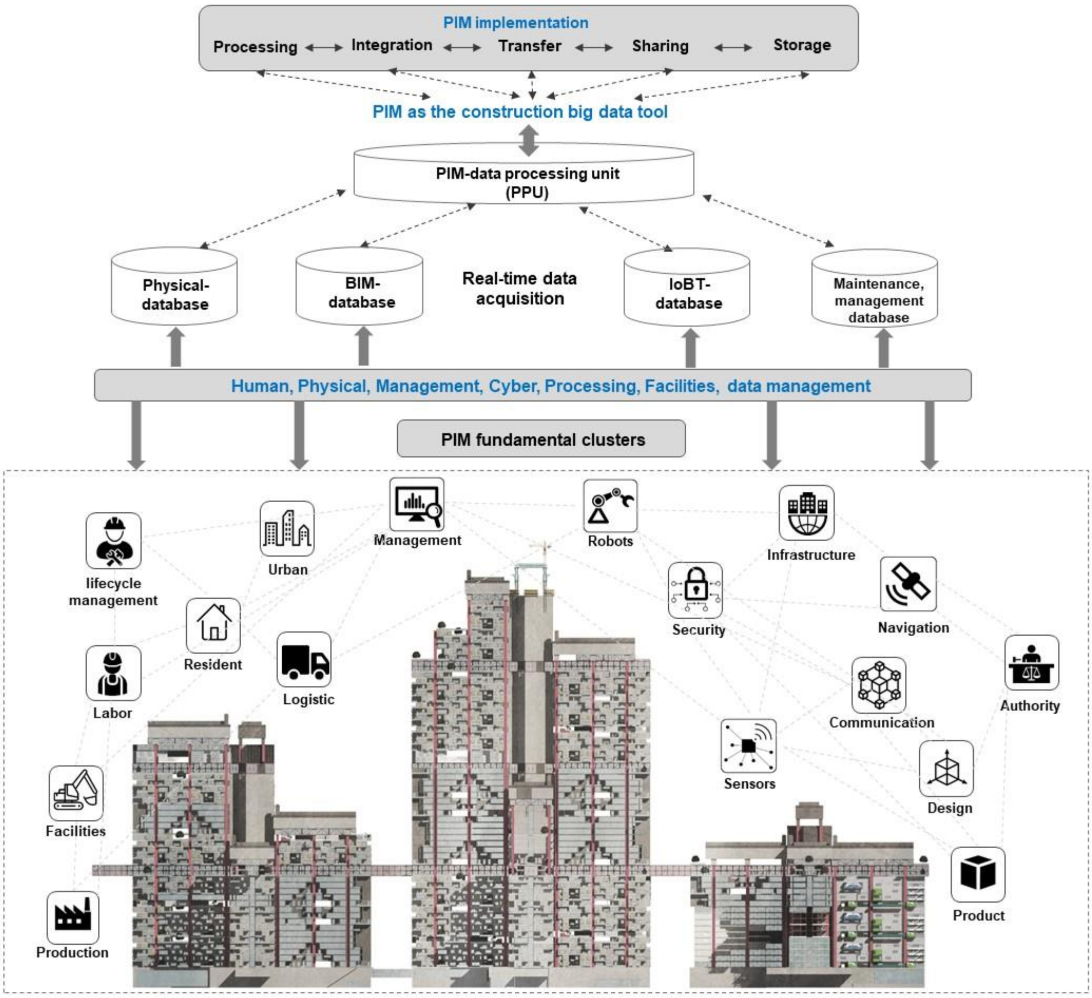

Figure 6-17: Proposed PIM framework to manage the entire life cycle of the proposed approach

6.2.7 Development scenario

In general, the construction of the building follows a bottom-up approach, working from the ground section up. The construction sequence consists of six main procedures: First, the assembly of the initial on-site construction factories; second, structural assembly, in which the steel beams, columns and the floor components are assembled; third, external façade finishing; fourth, service installation, and interior decoration; fifth, preparation or removal of the temporary installation fixtures, anchor systems; finally, the entire SCF will be jacked up by the self-climbing structure. The building component will be installed following a programed pattern. A specific sequence of crane and robot manipulations will occur, which is synchronized by the project control program. When reconfiguration of the building is required, the interior can be easily modified; when relocation and deconstruction are required, deconstruction can be conducted in a reversed order to the construction process. One possible scenario for the future development over the lifecycle of a complex following the principles of Dynamic Vertical Urbanism is envisioned in Figure 6-18 and the future vision of this complex is visualized in Figure 6-19 and Figure 6-20.

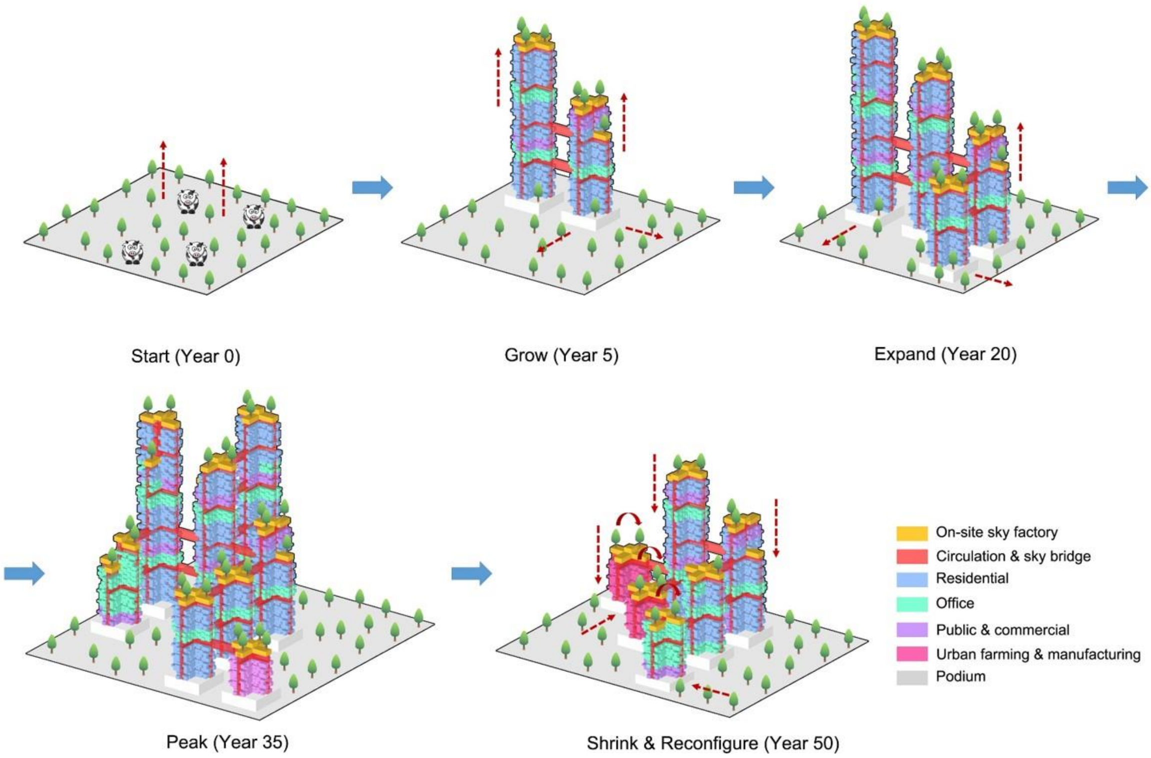

Figure 6-18: An exemplary scenario of 50-year development of a complex based on Dynamic Vertical Urbanism

Figure 6-19: Visualization of the roof garden of a dynamic vertical urbanist complex

Figure 6-20: The future vision of a Dynamic Vertical Urbanism complex in Shanghai's suburban context

6.3 Discussion

In this section, the limitations of the proposed framework, the future work to overcome them, and the novelty of this research will be discussed.

6.3.1 Limitations and future research

Like any other conceptual frameworks of building typology, this framework surely has its limitations, including: (1) The conceptual framework is not yet verified; (2) the feasibility of the integration of the subsystems (i.e., the "seven pillars" of Dynamic Vertical Urbanism) into one building system is not validated; (3) the proposed framework might have features that do not comply with current building code and regulations (e.g., early or continuous occupation of the building complex when it is under construction or expansion, novel construction methods which are not widely known or utilized in the current construction practice, etc.); (4) the cultural aspects of this framework in architecture are not yet discussed. Therefore, the next steps of the research should be conducted as follows.

(1) The framework should be further verified and optimized according to the feedback from the academia and industry. This would help to refine the proposed framework and theory based on the knowledge and experience of a broader audience.

(2) Conduct feasibility studies, partly or fully validating and implementing the proposed subsystems with potential pilot projects. The development of pilot projects will further attract industry deployment, introduce specialized construction equipment and multi-task construction robots, and enhance human-machine interaction within the construction industry to promote new measurement techniques improving work environment safety.

(3) As the validation phase progresses, the details of each subsystem must be examined and finetuned carefully in order to comply with the local building code and regulations. Furthermore, researchers, city planners, and policy makers should seek to improve the existing regulations and even establish new standards as a response to the rapid-changing construction technology, urban environment, and societal circumstances.

(4) The architectural design of each building complex must involve an in-depth understanding of the local context, including the natural environment, cultural practice, and aesthetic preference of the particular location. This endeavor can help to improve the acceptance of buildings based on the proposed framework.

6.3.2 Novelty

This chapter provides a bold reconsideration of vertical city in the name of Dynamic Vertical Urbanism, enabling constant vertical urban transformation by applying the state-of-the-art building theories and technologies. Six interconnected concepts and technologies constitute Dynamic Vertical Urbanism, including five city elements, Robot-Oriented Design, Open Building concepts, modularization and industrialized prefabrication, on-site automation, and Building Information Modeling. A novel framework of vertical city, or in other words, Dynamic Vertical Urbanism, covering the entire life cycle of a construction project and featuring constant vertical urban transformation by applying the state-of-the-art construction technologies is proposed. This chapter responds to RQ5 (i.e., how can the proposed system be integrated into future smart cities?).

This proposed framework demonstrates a significant first step to fill the research gap between current skyscraper projects broadly entitled "vertical cities" and the missing trait of a city, which is its ability to continuously grow and transform in terms of forms and functions. Furthermore, the framework is highly flexible and replicable so that architects and civil engineers around the globe are able to propose their own customized and localized interpretations of Dynamic Vertical Urbanism based on the seven-pillar principles. In addition, this research raises public awareness and promotes involvement for the research and development of construction automation and robotics. In the meantime, it can assist architects and urban planners to formulate a future framework for building design, urban planning, and policy-making process to benefit all potential stakeholders, and provide an inspiring way of thinking to tackle the aforementioned serious issues, such as overpopulation, population aging, land shortage, lack of infrastructure, and environmental pressures. More importantly, it is possible that the results of this research will potentially establish topic-specific or spin-off research areas in various disciplines. Finally, the principles of the proposed framework of Dynamic Vertical Urbanism (i.e., seven pillars) lay the foundations for the author's future research endeavors on various levels (e.g., urbanism, Robot-Oriented Design, Open Building principles, modularization and industrialized prefabrication, construction robotics, Process Information Modelling, and Ambient Assisted Living).

Nowadays, due to the improvement of medical care standards, the enhanced social security level, and the implementation of the three decade-long one-child policy which was recently replaced by the two-child policy since 2015, China is about to accelerate into an aging society (Zeng and Hesketh, 2016). Meanwhile, issues such as rapid urbanization, severe environment pressure, and increasing labor costs will further challenge the stability and sustainability of China's development. Given that the technical barriers for the popularization of construction automation technology have substantially diminished due to the rapid development of information technology and robotics, the construction automation technology will soon provide a great opportunity to tackle those critical issues. The proposed framework is meant to be tailor-made for the Chinese construction industry, but it will have wider audiences once the industry sector is ready to be reformed. For example, the future construction sector will expose a cross-disciplinary characteristic that will allow many industries and disciplines to coexist and collaborate. In this sense, upgrading the performance of the construction industry will not only have a positive impact on one industry, but also grant much larger contribution to the prosperity of many in the future (Bock, 2015).

7 Conclusion and future work

"Do not go gentle into that good night; Old age should burn and rave at close of day…"

Dylan Thomas[13]

In summary, this doctoral research first proposed a procedure model as the foundation to efficiently develop gerontechnology systems in a systematic manner (**SQ1: What is the suitable methodology to develop such a system?**). After, it started with introducing the population aging phenomenon and its consequences. Based on the analysis of the attitude changes towards robots and AI in sci-fi movies, the state-of-the-art ambient assisted living solutions, and the requirements of older adults, a service system transforming clinical and care environments into personalized modular sensing, prevention, and intervention systems was proposed, encouraging older adults to become healthier through various activities. To achieve that goal, a series of smart interior devices integrating advanced sensing and assistive technology, namely Personalized Intelligent Interior Units, were developed which seamlessly materialize the care concepts and functionality. Meanwhile, a flexible modular Ambient Rehabilitation Kit integrating abovementioned assistive technologies was proposed to create a unique interior living and care solution for older adults in various living environments. At the same time, a strategy for testing and exhibiting the system was proposed (**SQ2: What are the main components and functions of the proposed system?**). Furthermore, this research also explored a framework for the cost-benefit estimation of the Ambient Rehabilitation Kit compared to traditional care methods in three scenarios, whose results indicated that the proposed Ambient Rehabilitation Kit is worth investing by the healthcare system in Germany, soothing the labor shortage in the healthcare system (**SQ3: What is the financial performance of the proposed system?**). In addition, in order to mitigate the severe threat to China's social sustainability imposed by rapid population aging, the prospects for implementing the Ambient Rehabilitation Kit in China's market were discussed and a research and development action plan was proposed based on the results of an opinion survey (**SQ4: How can the proposed system be introduced to markets outside Europe?**). Finally, the proposed system was also integrated in a larger visionary context, namely Dynamic Vertical Urbanism, as an outlook for a comprehensive urban developing model for the future, powered by advanced construction and assistive technologies (**SQ5: How can the proposed system be integrated into future smart cities?**).

In conclusion, this thesis preliminarily proved the hypothesis of this doctoral research, which is that the Ambient Rehabilitation Kit developed efficiently with a systematic procedure

[13] Dylan Thomas (1914–1953): Welsh poet.

model can increase older adults' activity and independence level, liberate caregivers and relatives from tedious daily care and exercising tasks, and empower them to communicate on psychological and emotional level, eventually mitigating the impact of rapid population aging in in an affordable and scalable manner (**RQ: How efficient can the novel research field of Ambient Assisted Living help mitigate the crisis of population aging by increasing older adults' activity and independence level?**).

The work presented above synthesizes interdisciplinary knowledge and know-hows such as demography, systems engineering, geriatrics, industrial design, mechatronics, curating, finance, sociology, statistics, construction robotics, architecture, and urban design to create a comprehensive and continuous response to the social challenges imposed caused by aging society in a global perspective. Furthermore, this doctoral thesis not only is a thesis on the development of the Ambient Rehabilitation Kit, but also can be used by future researchers and engineers as a handbook on how to develop an automated technological solution for healthcare industry and beyond in a systematic manner.

7.1 Summary of the doctoral thesis

At the end of the thesis, a brief review of the whole work would be important. Therefore, key results and highlights of each chapter are summarized below (see Table 7-1).

Table 7-1: Key results and highlights of each chapter

Position in the thesis	Chapter topic	Key results and findings of each chapter
Chapter 1	Background	• The global population aging crisis and its consequences are discussed. • The situation of elderly care today was detailed. • The research questions and hypothesis were proposed. • The methodology of this doctoral research was described, and the structure of this thesis was outlined.
Chapter 2	Literature review	• Human's attitude towards robots, automation, and AI was discussed from the perspective of sci-fi movies. • The phenomenon of aging and the related common diseases were discussed. • The state-of-the-art of smart home approaches and their shortcomings are analyzed. • The latest R&D projects in the field of smart furniture were analyzed. • The research objectives based on the state-of-the-art technology was summarized.

Chapter 3	Development of an unobtrusive interdisciplinary approach to achieve demographic sustainability	• The methods for developing ambient rehabilitation such as interdisciplinary approach, system architecture, requirements engineering, and design principles were introduced. • The development of the PI^2Us was detailed. • The Ambient Rehabilitation Kit concept was proposed. • The strategy for the testing and exhibition of the Ambient Rehabilitation Kit was reported.
Chapter 4	Framework for the cost-benefit analysis of robotic and automated solutions	• The economic evaluation method of CBA was introduced. • A methodological framework for conducting CBA of robotic and automated solutions was proposed. • One of the first case studies of the CBA of STCRs (i.e., a cable-driven façade installation robot) was conducted. • One of the first case studies of the CBA of the smart home solutions (i.e., smart furniture in three different scenarios) was conducted.
Chapter 5	Survey and action plan for the Chinese market	• An opinion survey using the PI^2Us as an example to investigate the attitudes and opinions of Chinese older adults towards the smart home and smart furniture technology was conducted. • The survey results were analyzed, showing that Chinese older adults in general have a highly positive attitude towards smart furniture. • A three-year project action plan for developing elderly-oriented smart furniture technology in China was outlined.
Chapter 6	Framework for developing future smart cities based on state-of-the-art building technologies	• The research gap in “vertical city” and key learnings from several cities worldwide were discussed. • The key theories and technologies that can be applied in the development of future smart cities were analyzed. • A framework for developing future vertical cities based on state-of-the-art building technologies was proposed and visualized.
Chapter 7	Conclusion and	• The thesis was briefly summarized.

	future work	• Overall limitations and future work were discussed.

7.2 Overall limitations and future work

The work presented in this thesis laid the foundation for future iterations and improvements of the Ambient Rehabilitation Kit and beyond. The specific limitations were discussed respectively in each chapter. However, there are several aspects that have not been covered in this development cycle (see Figure 1-4). In the follow-up phase of the research, the main focus will be enhancing the usability of the prototypes, expanding the PI^{2}U family, establishing an entity to carry out a sustainable business model for the abovementioned innovations, seeking intellectual property protection for the key results, as well as seeking standardization of the components developed in this research in order to push them to the market in a sustainable manner. These future tasks constitute the components of the following iterations of the proposed procedure model. The cycle will be iterated over time until the optimal solution is found (see Figure 7-1).

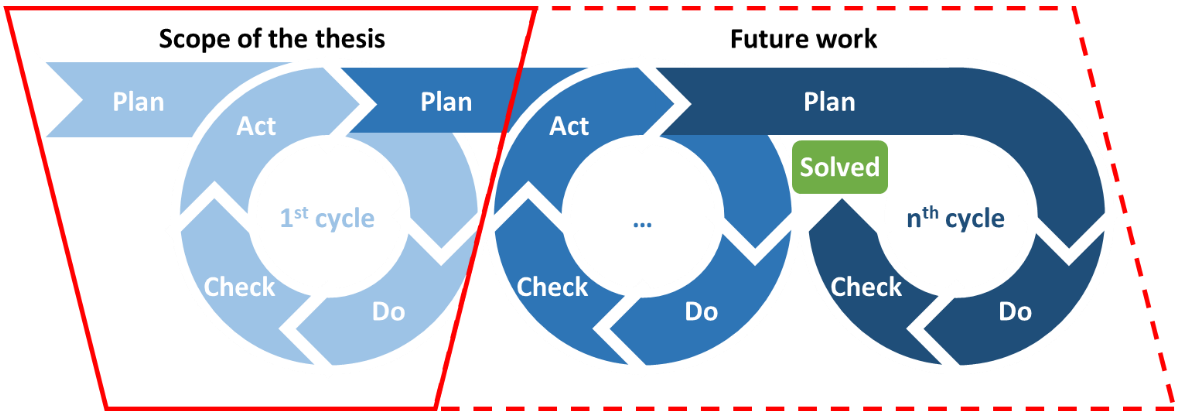

Figure 7-1: Perpetual development cycle to adapt to the situation (figure redrawn and adapted from Christoph Roser at AllAboutLean.com, licensed under CC BY-SA 4.0, https://creativecommons.org/licenses/by-sa/4.0/)

In the General Project Review Consolidated Report of REACH, the EU recommended that the research team shall continue the excellent work and focus on further leveraging the impact of the results. The report is not only a significant encouragement for the project team, but also a guideline for the future improvement of the aforementioned technology. Therefore, future tasks of the next iterations are listed including but are not limited to the aspects below.

7.2.1 Optimizing and expanding the PI^{2}U family (Do)

As aforementioned in the thesis, the continuous improvements of the developed PI^{2}Us are in progress. In the future design iterations of the prototypes, the work priority will be focused on enhancing the user experience of the PI^{2}Us together with end users. In order to meet the real needs of the older adults, design techniques such as persuasive principles need to be applied in this process (Valk et al., 2017). Furthermore, attributes of the PI^2Us such as usability, quality, privacy protection, affordability, multifunctionality, and aesthetics needs to be improved in order to appeal to more older adults.

In the meantime, new PI^2Us with additional functions and forms will be developed to expand the PI^2U family in order to appeal to a broader user group. For example, mobile robot, exoskeleton, unobtrusive wearables (e.g., wristwatch strap from Invis Wearables, ring, necklace, etc.) are worth further investigation. Furthermore, it is reasonable to also include and integrate the results from previous AAL projects from the Chair of Building Realization and Robotics at TUM (e.g., GEWOS, PASSAge, USA^2, LISA Habitec, BaltSe@nior, etc.) into the PI^2U family in order to provide a more comprehensive solution to the various challenges brought by aging society.

7.2.2 Quantitative studies (Check)

A quantitative usability test in home environment is important for developing the next improved iteration of PI^2U prototypes. Although five experts in related fields (e.g., engineering, fashion, medicine, business, education) were invited to TUM's testing apartment to test the functionality of the PI^2U prototypes from the perspective of older end-users, a user experience study involving more ordinary older adults is needed to test the usability of the prototypes in a quantitative manner in a simulated home environment (see Figure 7-2). Due to the restrictions posed by the COVID-19 pandemic, meaningful user experience study of the PI^2U prototypes is planned in the follow-up phase of the project after the pandemic, where more than 20 older adults ($n \geqslant 20$) will be recruited to test the prototypes' usability. This step is important for developing the next improved iteration of PI^2U prototypes. Aspects such as overall evaluation, functionality, ease of use, comprehensibility, aesthetics, and safety will be examined in Likert scale by the test participants.

Furthermore, it is also necessary to conduct similar usability test in other parts of the world when deploying the proposed technologies. As mentioned in Section 5.4.5, one of the top Chinese furniture manufacturers has already initiate a R&D project with the REACH start-up company to investigate the feasibility on the Ambient Rehabilitation Kit in the context of China. One of the key expected results is to build a localized showroom in a care home environment comprising the customized PI^2Us and other relevant technologies, where a usability study will also be conducted in the Chinese context. The results of the follow-up project will be revealed in future publications.

In addition to the usability tests, clinical trials to test the impact of the whole Ambient Rehabilitation Kit on the physiological indicators of older adults can also be conducted in future studies.

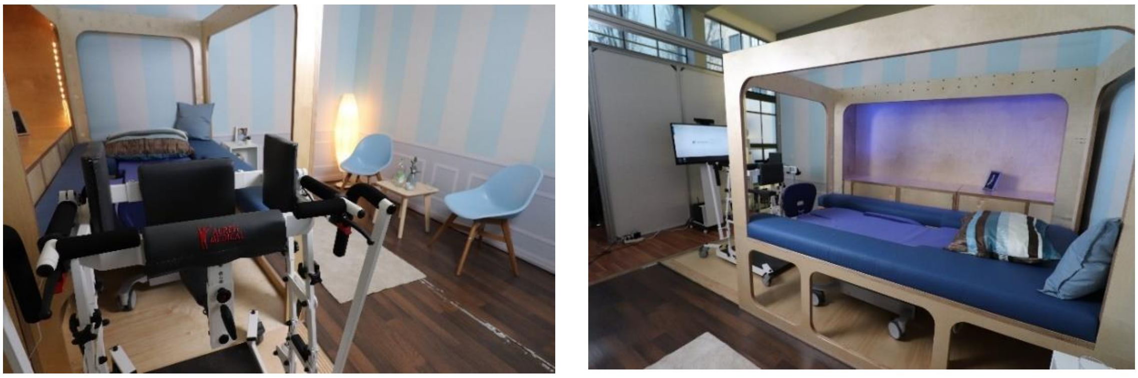

Figure 7-2: Home environment in the testing apartment at TUM's laboratory

7.2.3 Business model and knowledge transfer (Act)

Establishing the appropriate business strategy is the key to success of an innovation. A start-up company will be established to continue the exploitation of the experience and know-hows gained during R&D journey described in this thesis. Therefore, key members of the project are currently preparing the formation of a "REACH Active Ageing GmbH" which will serve beyond the project as an integrator of the project partners' individual products and services, and a solution provider to well-defined market segments based on suitable business models. Furthermore, as mentioned in Chapter 5, the preparation team of the start-up is currently preparing to cooperate with a large Chinese furniture manufacturer to promote the localization of elderly-oriented smart furniture technology in order to tackle the challenges imposed by rapid aging society. The results of the project will be revealed in future publications.

7.2.4 Intellectual property protection (Act)

In the scope of this thesis, an innovative Ambient Rehabilitation Kit comprising a series of original smart furniture devices (i.e., PI^{2}Us) was developed. Thus, suitable legal protection will be the key to continue the success of the products developed so far. In the next phase of the R&D process, the PI^{2}Us (e.g., SilverArc, MiniArc, SilverBed, etc.) including their installation process and user interfaces shall be protected through industrial designs and utility patents in respective countries in order to better push the developed systems into the market and sustain the motivation of innovation.

7.2.5 Towards standardization (Act)

Innovative products can easily wither if there is no access to the global market, even if they are appreciated by experts. The standardization activities play a sometimes invisible but crucial role in buttressing not only the competitiveness and social impact of innovations but also the economic growth of society. For example, standardization accounts for 0.9 % of the annual economic growth of Germany (Blind et al., 2011).

There are three standardization bodies that can facilitate the standardization of an innovation: national, continental, and international. On national level, different countries have different structures and standardization bodies. Each country can designate one standardization body to represent it on the international level. For example, Germany has German Institute for Standardization (DIN) as its national standardization body. On continental level, countries can be represented by additional standardization bodies. For example, there are European Committee on Standardization (CEN), the European Committee on Electrotechnical Standardization (CENELEC), and the European Telecommunication Standards Institute (ETSI) representing Europe on the European level. On international level, similar structures exist: the International Organization for Standardization (ISO), the International Electrotechnical Commission (IEC), and the International Telecommunication Union (ITU) (ISO, 2004).

Based on the experience and know-how gained in this research, the technical committee ISO/TC 314 – Ageing societies has been established to develop standards and guidance to tackle global challenges brought by aging society. Furthermore, in order to better suit the needs and preference of older adults, standards for developing Ambient Rehabilitation Kits can be further built on different standardization levels in other parts of the world to facilitate product localization and market optimization (e.g., in collaboration with ISO member body Standardization Administration of China, SAC).

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Appendices

Appendix I: Glossary

A

Activities of daily living (ADLs): Ordinary self-care tasks that people do daily such as dressing, cooking, eating, shopping, and showering.

Aging society: According to the World Health Organization, if the proportion of a society's population aged 65 or older exceeds 7%, it is defined as "aging society".

Aged society: According to the World Health Organization, if the proportion of a society's population aged 65 or older exceeds 14%, it is defined as "aged society".

Ambient assisted living (AAL): A young research area aiming at developing technologies for the ageing population in order to increase their safety, independency and comfort.

Architecture, engineering, and construction (AEC): The industry that provides building-related services such as architectural design, civil engineering, and construction.

Artificial intelligence (AI): "The theory and development of computer systems able to perform tasks normally requiring human intelligence, such as visual perception, speech recognition, decision-making, and translation between languages", according to Oxford Languages.

B

Benefit-cost ratio (BCR): A financial indicator revealing the relationship between the relative costs and benefits of a proposed project. If a project has a BCR greater than 1.0, the project is expected to deliver a positive net present value to its key stakeholders.

Body mass index (BMI): A measure of body fat based on height and weight applying to adult men and women, which is calculated with a person's weight in kilograms divided by the square of height in meters

Break-even point (BEP): The time point at which the total cost and total revenue are equal.

Building information modelling (BIM): A 3D digital modeling tool for modeling that controls a building project.

C

Cable-driven parallel robot (CDPR): A type of parallel robots that are driven by a set of flexible cables.

Cardiovascular disease (CVD): A general term for disorders affecting heart and blood vessels.

Chronic obstructive pulmonary disease (COPD): A chronic inflammatory lung disease that causes obstructed airflow from the lungs whose symptoms include breathing difficulty, wheeziness, cough, and phlegm production.

Computer-aided design (CAD): The use of computer programs to aid in creating, modifying, analyzing, or optimizing a design.

Coronavirus disease 2019 (COVID-19): A respiratory transmissible disease first identified in late 2019 caused by the SARS-CoV-2 virus.

Cost-benefit analysis (CBA): A policy assessment tool that monetizes all impacts of a project or policy to all relevant stakeholders in society.

Curtain wall module (CWM): A modularized building envelope unit that is designed to support only its own weight and withstand the effects of environmental forces such as wind.

D

Deadly quartet: Metabolic conditions including abdominal obesity, hyperglycemia, hypertension, and hypertriglyceridemia.

Dynamic Vertical Urbanism (DVU): A novel conceptual framework to develop future vertical city based on advanced building technologies such as construction automation, open building principles, industrialized prefabrication, process information modelling, and ambient assisted living.

E

Electrocardiography (ECG): A common and painless test that checks how individual's heart is functioning by measuring the electrical activity of the heart.

Electromyography (EMG): An electrodiagnostic medicine technique for evaluating and recording the electrical activity produced by skeletal muscles.

G

Gerontechnology: A cross-disciplinary research and development field combining gerontology and technology.

Global South: The regions of Asia, Africa, Latin America, and Oceania that are usually underdeveloped.

Graphical user interface (GUI): A type of user interface which allows users to interact with systems via graphical icons and sound indicators, instead of command-line interfaces.

Gray Rhino: A highly probable, high-impact threat, defined by American author Michele Wucker.

I

Information and communications technology (ICT): A expanded term for Information

Technology (IT) which refers to all communication technologies such as the internet, wireless networks, computers, smartphones, software, middleware, video conferencing, social networking, and other media applications and services enabling users to access, obtain, utilize, transfer, store, and manipulate information in a digital manner.

Intensive care unit (ICU): A special unit of a health care facility that provides intensive care medicine to patients with severe diseases or injuries.

K

Kuhn Cycle: A simple cycle of scientific progress described by philosopher Thomas Kuhn in which he challenged the notion that scientific progress was the incremental accumulation of new knowledge, and argued that science progressed the most by occasional revolutionary novel ways of thinking, or in other words, new paradigms.

L

Life support system (LSS): According to Britannica, LSS means "any mechanical device that enables a person to live and usually work in an environment such as outer space or underwater in which he could not otherwise function or survive for any appreciable amount of time".

Light-emitting diode (LED): A semiconductor light source that emits light when current flows through it.

M

Margin of error (MOE): A statistical term describing the maximum amount of the sample results deviating from the real values.

N

Net present value (NPV): The value of a sum of money in the present compared to the future value it will have if it has been invested at compound interest.

O

Organisation for Economic Co-operation and Development (OECD): An intergovernmental economic organization with 37 member countries, most of which are high-income economies with a very high Human Development Index (HDI) and are often considered as developed countries.

P

Payback period (PBP): The time needed to recover the funds expended in an investment, or in other words, the time to reach the break-even point.

Personalized Intelligent Interior Unit (PI^{2}U): Smart furniture which is used to integrate various functionality seamlessly into the different use case settings. In a broader sense, PI^{2}Us will mainly materialize as furniture pieces that can be placed and moved within a particular environment or setting (e.g., beds, bathroom furniture, mobile walkers/standers, large-scale interfaces, smart flooring tiles, smart tables, etc.). Additionally, PI²Us will also appear as ambient sensor add-on modules and wearables.

Plan-Do-Check-Act (PDCA): A cyclic four-step management model used in business to control and continuously improve processes and products. It is also sometimes referred to as the Deming Cycle.

Potential support ratio: The ratio of the population aged 25-64 to the population aged 65 years or over.

Process information modeling (PIM): The next generation BIM that will enhance information integration and emphasize on the process of each construction tasks as well as the relationship between them.

Programmable logic controller (PLC): A ruggedized computer that is developed for industrial automation.

Q

Quality of life: "An individual's perception of their position in life in the context of the culture and value systems in which they live and in relation to their goals, expectations, standards and concerns", as defined by the World Health Organization.

R

Random-access memory (RAM): A type of computer memory that can be accessed and modified rapidly by the processor in any order. The data stored in RAM will be lost if power is removed.

Radio frequency identification tag (RFID): RFID is a low-cost tag used to attach to components, modules, units, or products, which can be read by RFID readers for object identification. Advanced readers can read multiple tags at the same time.

Research and development (R&D): A series of innovative activities undertaken by corporations or public organizations in developing new services or products and improving existing ones.

Return on investment (ROI): A performance indicator used to assess the profitability or efficiency of an investment.

Robot-Oriented Design (ROD): ROD is the design concept that before the final on-site construction process, all parameters shall have been already considered at the earlier design and production stages based on the characteristics of construction robots.

S

Severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2): The novel coronavirus that causes coronavirus disease 2019 (COVID-19).

Silver economy: The economic activities emerging from the public and consumer spending associated with population aging and the specific needs of older adults.

Single-task construction robot (STCR): A system that supports construction workers in excuting one specific construction task or process (e.g., concrete leveling, façade painting, curtain wall installation, bricklaying, etc.) or substitutes the physical activity of human workers that would be necessary to perform one task or process.

Smart home: A home equipped with lighting, heating, and electronic devices that can be controlled remotely by smartphone or computer.

Super-aged society: According to the World Health Organization, if the proportion of a society's population aged 65 or older exceeds 21%, it is defined as "super-aged society".

T

Technical readiness level (TRL): A type of measurement system used to evaluate the maturity level of a specific technology with TRL 1 the lowest and TRL 9 the highest.

Thermal camera: A device that forms a heat zone image using infrared radiation, similar to a common camera that forms an image using visible light.

Total dependency ratio: The ratio of the population aged 0-24 and that aged 65+ to the population aged 25-64.

Touchpoints: The "Touchpoints" will act as "graspable" front ends towards the end users (i.e., older adults). The Touchpoints will serve as data gathering devices and as mediators of services and interventions coordinated by the Engine towards the end user. Each Touchpoint is modular and made up of several subsystems which allow adapting the system both for a particular person or setting, as well as over time.

Touchpoints/Engine concept: The concept that structures the envisioned REACH product-service-system architecture into manageable research and development clusters.

U

Use case setting: It refers to the solution operators where concrete application scenarios were implemented and the corresponding tests were conducted.

V

Virtual reality (VR): A technology that provides close-to-reality or unreal experiences in a simulated manner.

W

Wearable technology: It refers to smart electronic devices that can be worn on user's body in order to detect, monitor, analyze, and transmit body signals such as vital signs and movements to promote users' well-being. Common examples include smart bands, smartwatches, smart glasses, smart clothes, smart footwear, and smart jewelry.

World Health Organization (WHO): A specialized agency at the United Nations that is responsible for international public health.

Z

Zigbee: A low-cost, low-power, low-latency, wireless mesh network standard that is suitable for wireless control and monitoring applications of battery-powered devices.

Appendix II: List of publications

<u>Book chapters:</u>

- Linner, T., Schmailzl, M., Bock, T., **Hu, R.**, & Güttler, J. (2022). Active Assisted Living Technology in the Context of the Built Environment. Companion to Ecological Design Thinking in Architecture & Urbanism. London: Routledge, Taylor & Francis.
- Linner, T., **Hu, R.**, Iturralde, K., & Bock, T. (2022). A Procedure Model for the Development of Construction Robots. Innovation in Construction - A Practical Guide to Transforming the Construction Industry. London: Springer Nature.
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<u>Journal articles (peer-reviewed):</u>

- Iturralde, K., Feucht, M., Illner, D., **Hu, R.**, Pan, W., Linner, T., Bock, T., Eskudero, I., Rodriguez, M., Gorrotxategi, J., Izard, J.-B., Astudillo, J., Cavalcanti Santos, J., Gouttefarde, M., Fabritius, M., Martin, C., Henninge, T., Normes, S. M., Jacobsen, Y., … Elia, L. (2022). Cable-driven parallel robot for curtain wall module installation. Automation in Construction, 138, 104235. https://doi.org/https://doi.org/10.1016/j.autcon.2022.104235
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- **Hu, R.**, Pan, W., & Bock, T. (2020). Towards dynamic vertical urbanism: A novel conceptual framework to develop vertical city based on construction automation,

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- Linner, T., Pan, W., **Hu, R.**, Zhao, C., Iturralde, K., Taghavi, M., Trummer, J., Schlandt, M., Bock, T. (2019). A technology management system for the development of single-task construction robots. Construction Innovation, 20(1). https://doi.org/10.1108/CI-06-2019-0053
- Linner, T., **Hu, R.**, Pawlitza, K., Güttler, J., & Bock, T. (2017). Systems engineering for prevention-oriented, assistive technology situated in a multidisciplinary context. Special Issue Journal of Gerontechnology 4/2017.
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Developing a Smart Home Solution Based on Personalized Intelligent Interior Units to Promote Activity and Customized Healthcare for Aging Society

Author: Rongbo Hu et al

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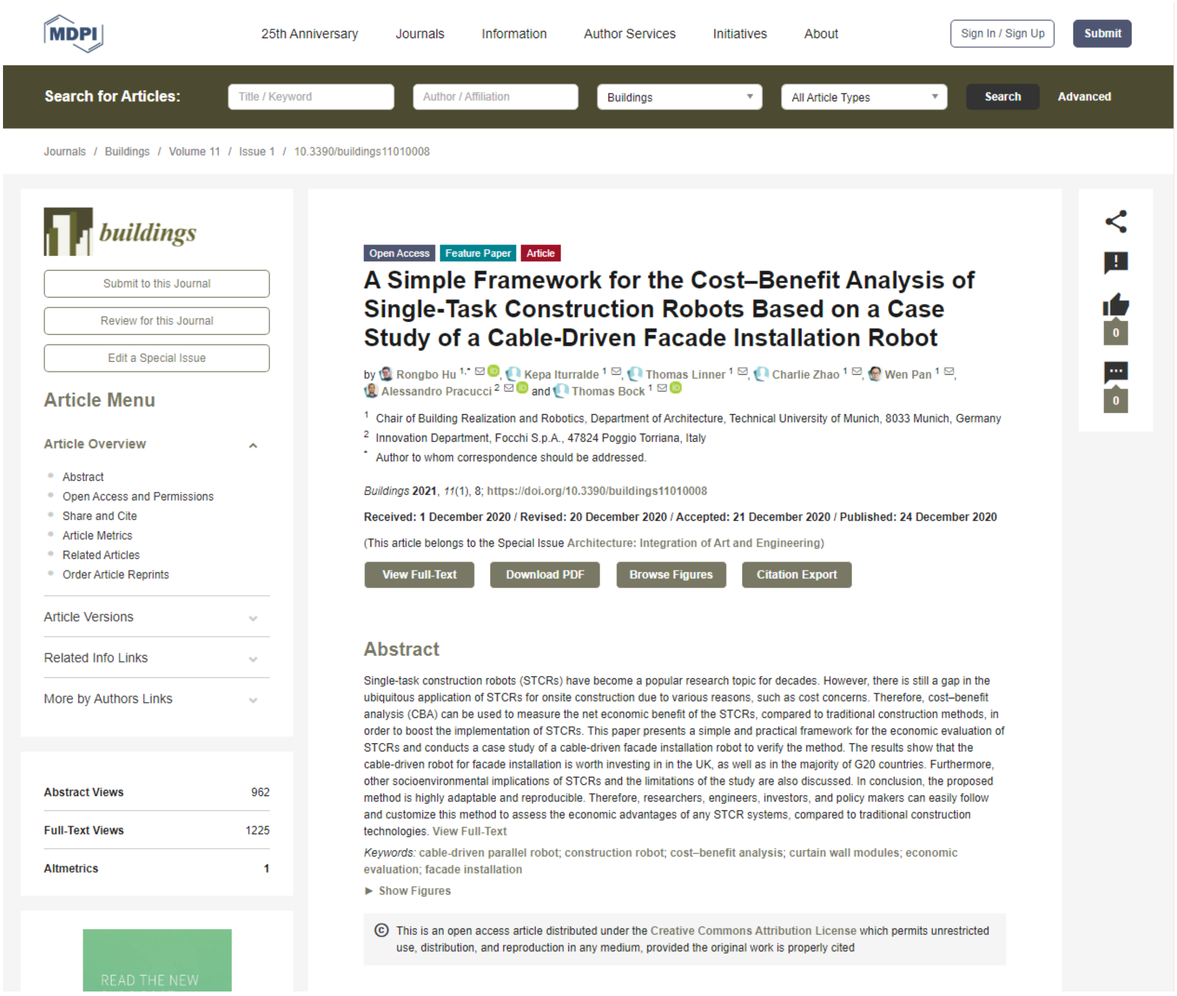

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A Simple Framework for the Cost–Benefit Analysis of Single-Task Construction Robots Based on a Case Study of a Cable-Driven Facade Installation Robot

by Rongbo Hu [1,*], Kepa Iturralde [1], Thomas Linner [1], Charlie Zhao [1], Wen Pan [1], Alessandro Pracucci [2] and Thomas Bock [1]

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Abstract

Single-task construction robots (STCRs) have become a popular research topic for decades. However, there is still a gap in the ubiquitous application of STCRs for onsite construction due to various reasons, such as cost concerns. Therefore, cost–benefit analysis (CBA) can be used to measure the net economic benefit of the STCRs, compared to traditional construction methods, in order to boost the implementation of STCRs. This paper presents a simple and practical framework for the economic evaluation of STCRs and conducts a case study of a cable-driven facade installation robot to verify the method. The results show that the cable-driven robot for facade installation is worth investing in in the UK, as well as in the majority of G20 countries. Furthermore, other socioenvironmental implications of STCRs and the limitations of the study are also discussed. In conclusion, the proposed method is highly adaptable and reproducible. Therefore, researchers, engineers, investors, and policy makers can easily follow and customize this method to assess the economic advantages of any STCR systems, compared to traditional construction technologies. View Full-Text

Keywords: cable-driven parallel robot; construction robot; cost–benefit analysis; curtain wall modules; economic evaluation; facade installation

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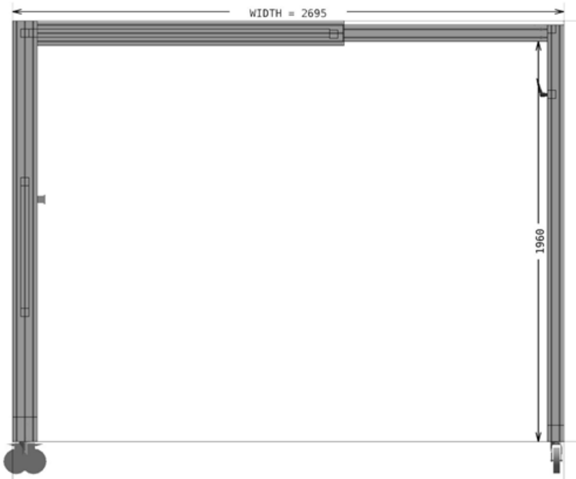
Appendix IV: Technical drawings of the PI²U prototypes

- SilverArc



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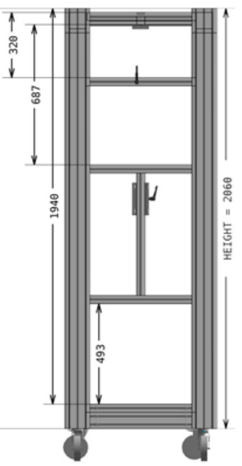

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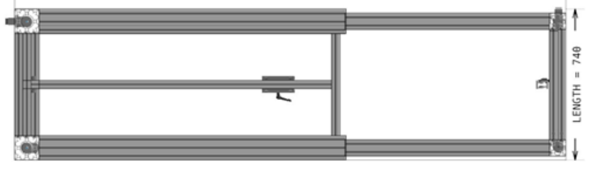
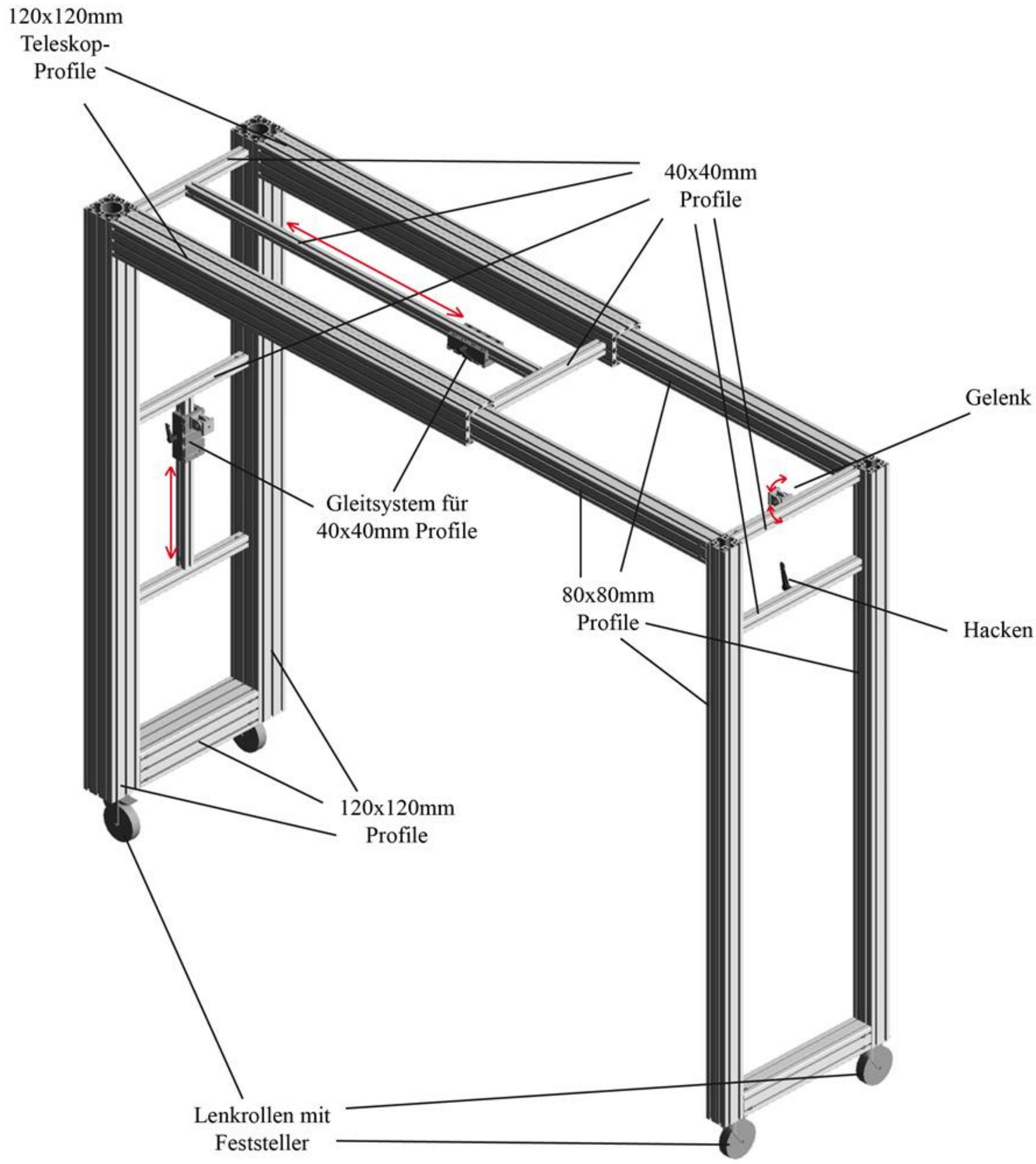
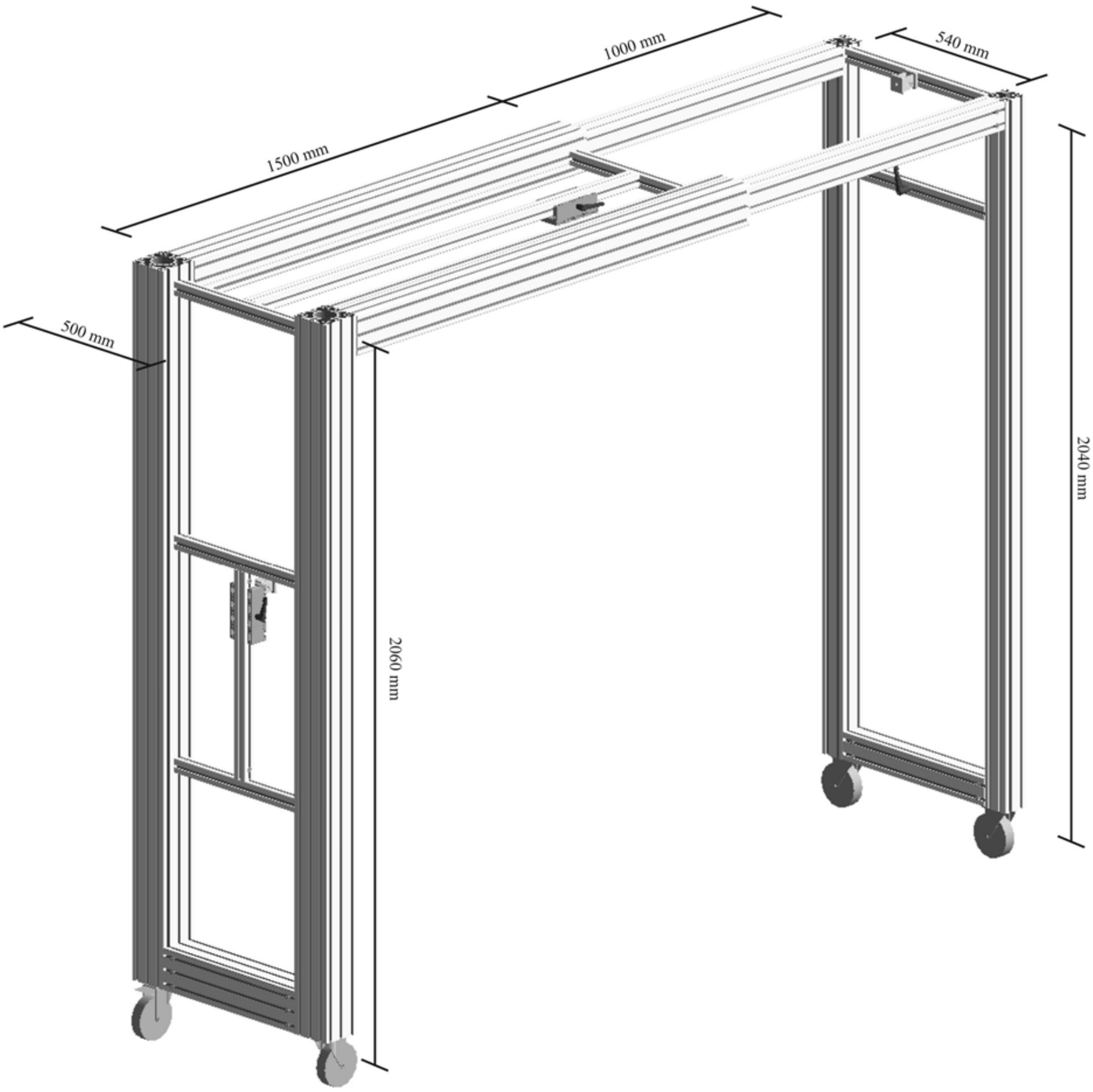


Draufsicht

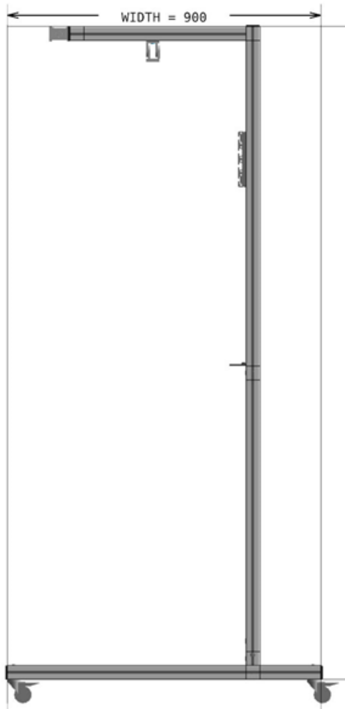
Isometrie



120x120mm
Teleskop-
Profile
40x40mm
Profile
Gelenk
Gleitsystem für
40x40mm Profile
80x80mm
Profile
Hacken
120x120mm
Profile
Lenkrollen mit
Feststeller


1000 mm
540 mm
1500 mm
500 mm
2040 mm
2060 mm

- MiniArc:



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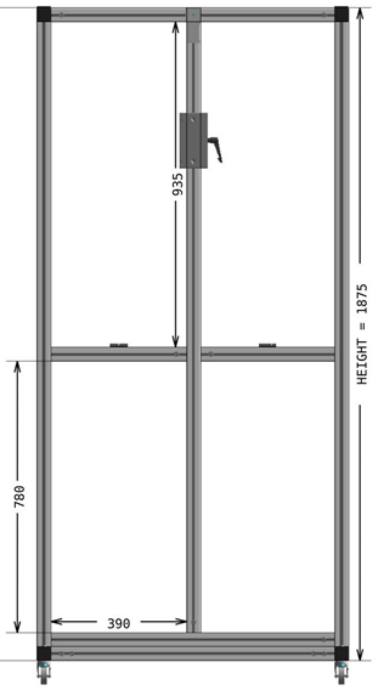

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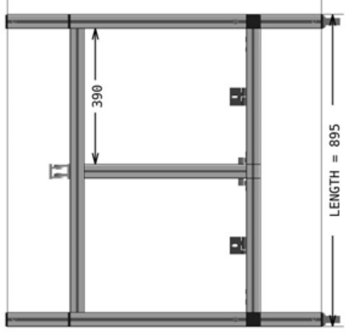

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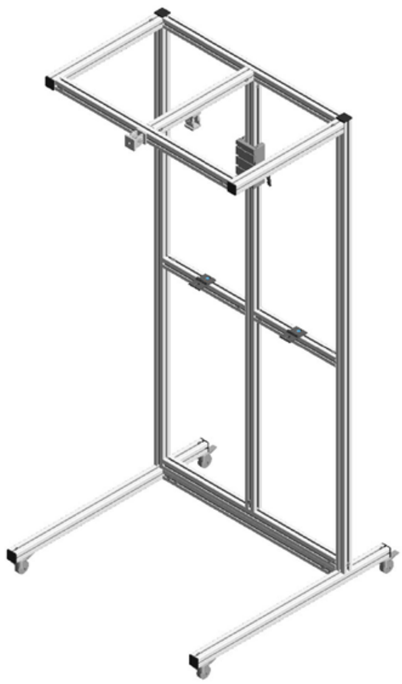

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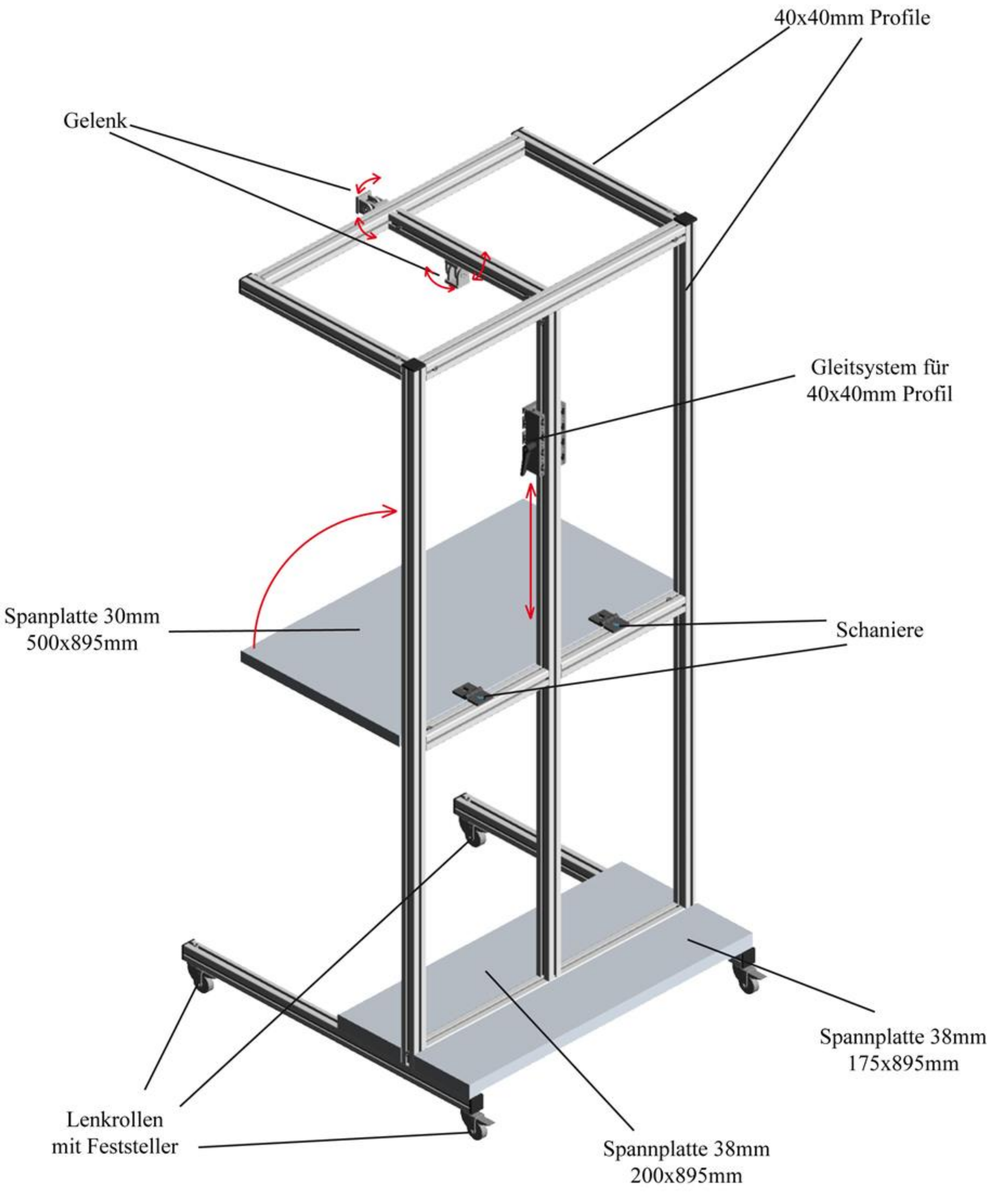
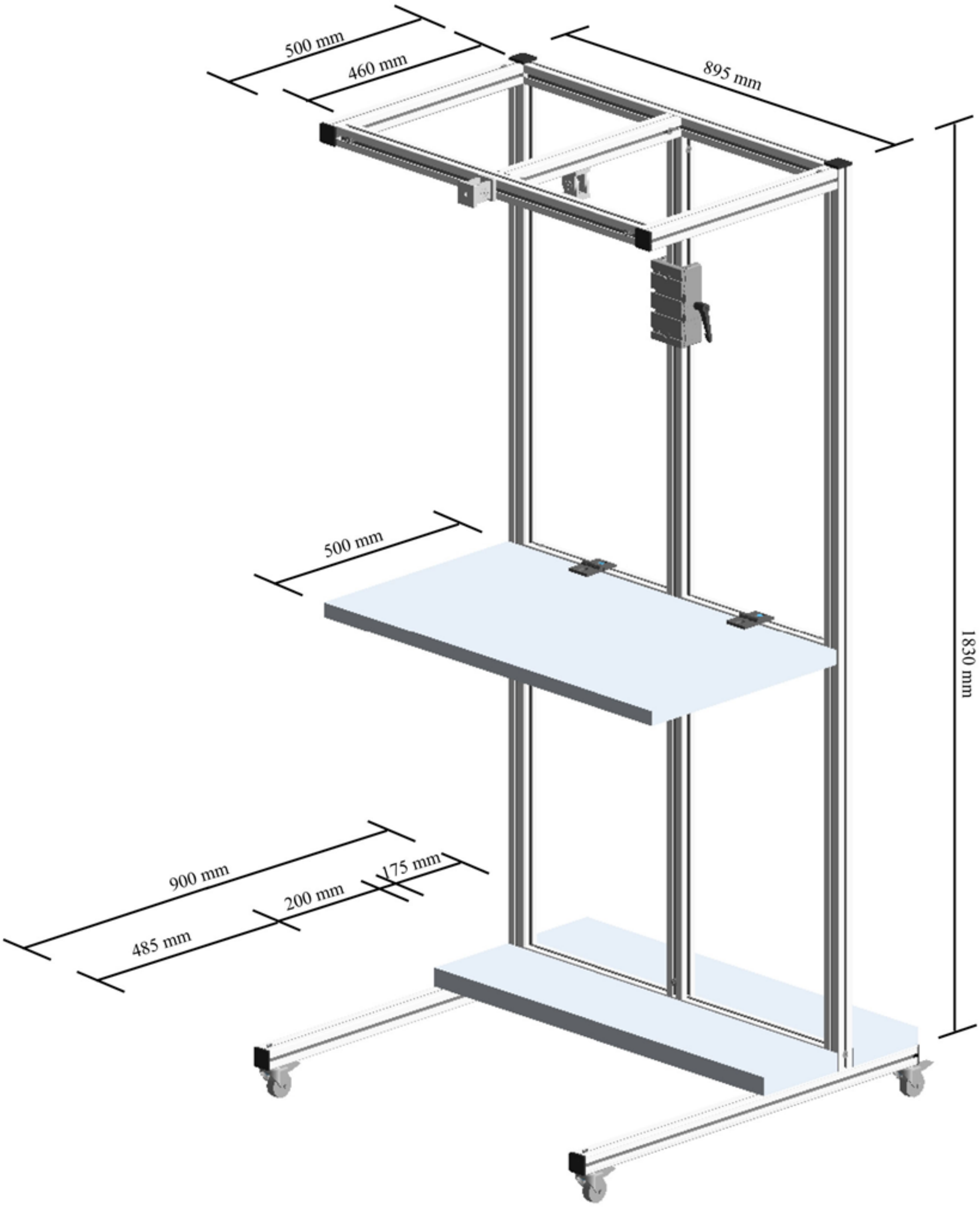

40x40mm Profile
Gelenk
Gleitsystem für
40x40mm Profil
Spanplatte 30mm
500x895mm
Schaniere
Spannplatte 38mm
175x895mm
Lenkrollen
mit Feststeller
Spannplatte 38mm
200x895mm


500 mm
460 mm
895 mm
1830 mm
500 mm
900 mm
175 mm
200 mm
485 mm

- SilverBed