From task allocation towards resource allocation when optimising assembly systems

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Abstract

The article discusses the question; *is it possible to reach route flexibility and system proactivity through resource allocation and task optimisation?*

In order to answer this, differences between three types of optimisations regarding task and resource allocation are discussed.

- Global Task and Resource optimisation
- Task optimisation and local resource allocation, but with resource alternatives
- Task optimisation and local resource allocation (optimisation), with prioritised resources, shown as a possible solution in this paper in order to increase the route flexibility and proactivity in the system planning.

An example of the last approach will be shown using a logic language with help of a software tool called Sequence Planner (SP)

Keywords:
Sequence planning, Resource allocation, Assembly systems, Levels of Automation

1 INTRODUCTION

To meet the demands on mass customisation, companies have to have a dynamic proactive and flexible production system. In order to handle the planning behind such a system, the sequences of tasks and products through the system can be optimised by computers using optimisation algorithms. In order to do this, the system itself has to be well defined and modelled by a human expert. This human expert, helped by different software tools, is required to create (pre and post) conditions for products, tasks and resources in the system. The aim of these (pre and post) conditions is to express only the minimal requirements when defining interfaces and precedence relations between tasks or availability and need for a specific resource; then the resource allocations and tasks can be efficiently optimised.

Time is not always the best criterion to consider when doing an optimisation. If the planning system is aiming to produce only what is necessary rather than maximising the number of products it is possible to optimise towards resource allocation i.e. the resource best suited to assemble will assemble not necessarily the fastest. Furthermore, if the main resource is not available, it is desirable to be able to re-plan (if desirable) and allocate the task to the next best resource i.e. route flexibility.

Route flexibility could be defined as;" The ability to reroute a product's path"[1]. This could be explained from a resource point of view and a product point of view:

Resource view: To use an operation as an alternative manufacturing step in another production group, if the usual operation and production group are: unavailable or unusable [2], due to a tool- or a machine breakdown [3, 4] or under-capacity [3].

Product view: To produce a multitude of products and handle changes in production planning [5].

Another criterion that is important to consider when allocating tasks and optimising a system is the ability to create proactivity. According to Frese and Fay [6], the focus in design or planning concepts often lies on reactive performance concepts, where static task allocation is performed. Occurring needs and solutions become responses to existing problems, i.e. highly reactive actions. It is questionable whether the reactive approach is sufficiently progressive and competitive. Instead, assembly systems need to be dynamic and evolvable to really constitute long-term assets for the manufacturing company [7]. Proactivity is defined as:

"The extent to which the individual takes self-directed action to anticipate or initiate change in the work system or work roles [8]"

The main issue considered in this paper is: *is it possible to reach route flexibility and system proactivity through resource allocation and task optimisation?*

In order to answer this hypothesis two research questions (RQs) are formulated:

RQ 1: What parameters need to be defined in order to perform task and resource allocation optimisations?

RQ 2: How can we define the best conditions for proactivity and route flexibility in the system?

In order to answer these questions, different scenarios will be discussed and an example of one of the approaches will be shown using a logic language with help of software called Sequence Planner (SP)[9].

2 DEFINITION OF DIFFERENT ALLOCATION APPROACHES

In order to optimise a system, allocation of operations to different resources must be considered. In most modern workplaces there is a close sharing of tasks between human operators and machines (technique) [10]. Throughout history there have been numerous definitions regarding how and when to allocate a task or a function and to whom, man or machine?

One of the most common and debated attempt to allocate different tasks to different resources is Fitts list from 1951 [11] which describes humans and machines differences. Fitts [11] thought that using the criteria in his list as the sole determinant of the allocation of functions was to lose sight of the basic nature of a system containing humans and machines. The Fitts list had little impact on engineering design practice because such criteria are overly general, non-quantitative, and incompatible with engineering concepts, and because they assume that functions will be performed by humans or machines alone [10]. Jordan [12] argued whether you could actually compare men and machines; and that the two should be seen as complementary, rather than conflicting resources when designing a man-machine system. Sheridan [13] suggested to “allocate to the human the tasks best suited to humans and allocate to the automation the task best suited to it”. It is only when both human and machine can do the same task, the question of task allocation becomes an issue [14]. Contrary to the widely accepted urge towards autonomy, the real need is to provide an organic relationship for mutual benefit between the human and the machine [15].

There are three different allocation approaches that are used in different stages and at different levels at companies; (1) static and dynamic (adaptive) function allocation [16]; (2) task allocation, concentrated on agents and multi robot systems [17-20] and human centered task allocation [21, 22] and (3) resource allocation [23, 24]. Two of them task- and resource allocation will be further explained below:

Task allocation is usually made later, often during system implementation [25]. This type of allocation is often a static allocation based on global optimisation [26]. Suitable allocation of tasks between resources (human operators and machines) and techniques have to be made and must be able to be dynamically changeable over time [27-29].Different tasks could have multiple resources suitable for it. Generally, the manufacturing requirements of the product need to be matched to the capabilities of actual resources. This product/resource mapping means that one or more possible resources are identified for each product operation. The desired degree of flexibility will decide how many alternative resources that are included in this resource allocation. Among the possible ones, a final choice has to be determined, e.g., by optimization [9].

The resource allocation can be based on a simplistic model such as available/unavailable resources. Such a model can be easily applied if we suppose that there is no resource breakdown, no maintenance task, etc. In that case, a resource could be allocated to an operation as soon as it is available.

3 COMPARING THREE APPROACHES WHEN OPTIMISING AND ALLOCATING TASKS AND RESOURCES WITHIN A SYSTEM

In order to answer RQ 1, three different approaches will be discussed when it comes to optimisation and allocation of tasks (i.e. the product view of route flexibility) and resources (i.e. the resource view of route flexibility). Furthermore these three approaches will be discussed in terms of how the parameters tasks and resources (i.e. humans or robots) will be defined.

1. Global optimisation (containing both tasks and resources) (illustrated as **X** in Table 2) [9, 30]. In this first approach both the needed tasks and the needed resources are optimised at the same time according to the some constraint, often in terms of cycle time.

The two other approaches are divided into 2a and 2b because the task optimisation is the same but the local task allocation differs.

2a. Task optimisation and local resource allocation *with resource alternatives* (illustrated as **Y** in Table 2) [31]

2b. Task optimisation and local resource allocation *with prioritised resources* (**ranking of the resources (R1-R5) from 1 to N, *where* N=4**).

Table 2 shows a summary of the three approaches with regard to how they handle tasks and resources.

Tasks/Resources	R1	R2	R3	R4	R5
Place A	X Y 1	Y 2		Y 3	4
Place B	Y 1	X Y		Y 3	4
Fixate A			X Y 1		
Fixate B			X Y 1		
Assemble A+B	4	Y 3		X Y 1	Y 2
Inspect A+B	Y 1	4		X 2	Y 3

Table 2 Summary of the three allocation approaches

Depending on what approach that is chosen, the result from a resource flexibility perspective will differ. The following sections will explain each optimisation and allocation approach, plus pros and cons with each solution.

3.1 Global optimisation

This first approach is based on a global optimisation of the sequence of operations. This optimisation is performed taking into account all pre- and post-conditions that are defined, from product design conditions to resource booking conditions.

Global optimisation can be performed according to various criteria, but time is the mainly used criterion [26].

The main advantage of this approach is that the optimised solution obtained corresponds to the global minimum of a cost function. Thus, this solution is the best we can get for the given context.

However, obtaining the optimal solution may need numerous computations. When the size of the system that must be optimised increases; the complexity of the optimisation problem increases too, in the worst case exponentially.

Furthermore, the “quality” of the optimal solution we obtained depends on the “quality” of the model used to perform the optimisation. The more precise and realistic the model is, the more realistic the optimal solution is. Unfortunately, to define a more realistic model, lots of additional information must be added to this model, what also increase complexity of the optimisation problem.

For large systems, obtaining such an optimal solution can take hours of computation. If an unexpected event occurs (robot breakdown, etc.), the optimisation needs to be performed again to find a new optimal solution. Thus, this decreases the flexibility of the assembly system.

Tasks/Resources	R1	R2	R3	R4	R5
Place A	X				
Place B		X			
Fixate A			X		
Fixate B			X		
Assemble A+B				X	
Inspect A+B				X	

Table 3 Global Task and Resource optimisation

Pros with alternative 1 are that it could be done early in the process and if the company only has one alternative resource for each task.

Cons could be that the result of the global optimisation is more or less static and is hard to change later in the process; it is also a risk for “left-over automation” [32].

3.2 Task optimisation and local resource allocation *with resource alternatives*

A way to tackle unexpected events is to take into account several alternatives for the resource allocation. A solution is to consider alternatives with different Levels of Automation.

In this approach a task optimisation is performed taking into account all pre- and post-conditions except those related to resource booking. Then, each operation is allocated to a set of alternative resources. When it is possible, alternative resources should be chosen among different LoA. In this example, R1 and R2 are high-LoA resources whereas R4 and R5 are low-LoA resources.

In this approach, none of the resource alternatives is prioritised. When the system is executing, the first resource available among the alternatives is allocated to the current operation. Since all alternatives are considered in the same way, the human resource is not considered as a “replacement” resource.

These resource alternatives permit to increase route flexibility of the system. Since alternatives consider different LoA, this approach also permits to increase proactivity.

On the other hand, since the resource allocation is done locally, it doesn’t permit to conduct a global optimisation. This implies that the obtained planning may not be optimal according to a time optimisation criterion.

Tasks/Resources	R1	R2	R3	R4	R5
Place A	**Y**	**Y**		**Y**	
Place B	**Y**	**Y**		**Y**	
Fixate A			**Y**		
Fixate B			**Y**		
Assemble A+B		**Y**		**Y**	**Y**
Inspect A+B	**Y**				**Y**

Table 4 Global task optimisation with resource alternatives

Pros for alternative 2 are also that it could be done early in the process if companies have few known resources to choose from that is known. It gives a little more dynamic due to changes later in the process. If there are a robot and a human to choose between it becomes more dynamic.

Cons with alternative two are that if companies solely want to optimize the system with throughput time as constrain since it focus on flexibility and proactivity.

3.3 Task optimisation and local resource allocation *with prioritised resources*

This approach is an extension of the previous one. The general idea is the same: a task optimisation is performed without taking into account resource booking condition, and then resources are allocated to different operations.

Contrary to the previous approach, resources are prioritised according to a ranking matrix. Different ranking matrices can be defined according to the different policies that can be applied: time, route flexibility, volume flexibility, etc. Fasth [33-35] have developed a LoA matrix, where the physical and cognitive Level of Automation (LoA), current and future needed, could be illustrated and analysed. However, it is common that designers automate every subsystem that leads to an economic benefit for that subsystem and leave the operator to manage the rest [36], to avoid this a global optimisation on task level has to remain.

Generally, the manufacturing requirements of the product need to be matched to the capabilities of actual resources. This task/resource mapping means that one or more possible resources are identified for each task. The desired degree of flexibility will decide how many alternative resources must be included in this resource allocation. Among the possible ones, a final choice has to be determined, e.g. by optimisation [9].
There is a need for a dynamic allocation that can take advantage of the access to instantaneous evaluation of the situations to choose the best allocation [37].
A case study that uses dynamically changeable Levels of automations (LoAs) [38] shows that it is possible to change from a human operator to a robot-cell and vice versa in order to achieve volume and route flexibility. The issue to be shown in this paper is how to model and simulate this dynamic allocation when alternative resources could be allocated to some operations. Difference in LoA implies that different resources need to be modelled as precisely as possible so that these models correspond to these LoA and not to a global resource. Furthermore, models of behaviour, knowledge and skills for robots and human must be considered in different ways in order to better fit the real resources.
For this example, if we consider operation *Place A*, R1 is the most prioritised resource and R5 the least. This implies that, as soon as R1 is available when operation Place A must be performed it will be allocated to. R5 will be allocated to Place A, only if all other resources (R1, R2 and R4) are not available.

The definition of these ranking matrices can be based either on an expert approach or on simulation results.

In this approach, alternatives resources permit to improve system flexibility and proactivity. The obtained planning may still not be optimal according to total assembly time but the worst solutions can be avoided using priority.

Tasks/Resources	R1	R2	R3	R4	R5
Place A	**1**	**2**		**3**	**4**
Place B	**1**	**2**		**3**	**4**
Fixate A			**1**		
Fixate B			**1**		
Assemble A+B	**4**	**3**		**1**	**2**
Inspect A+B	**1**	**4**		**2**	**3**

Table 5 Global task optimisation and local resource allocation

Pros for alternative 3 are the opportunity to allocate resources, considering not only time as a parameter but also different states and to make the system more flexible and proactive by ranking resources suitable for the task.

3.4 Summary of the of the approaches

In order to increase route flexibility from both a product and resource point of view when planning a system, global optimization will not be the best solution. We propose solution 2b, as the best suited solution for a proactive and more flexible system.

The following sections will explain how this approach can be defined using a logic language and finally apply it on an example using the proposed software.

4 HOW CAN WE DEFINE THE BEST CONDITIONS FOR PROACTIVITY AND ROUTE FLEXIBILITY IN A SYSTEM?

The resource allocation can be based on a simplistic model such as available/unavailable resources. Such a model can be easily applied if we suppose that there is no resource breakdown, no maintenance task, etc. In that case, a resource could be allocated to an operation as soon as it is available. However, this simplistic model cannot be used to represent a realistic assembly systems, especially if this assembly system is composed of both human and robots resources. To be more realistic, and in order to express the behavior of human and robot resources over a long period of time, “the state” of each resource can be represented using “operating modes”. For instance, a robot resource model can be composed of the five following modes: *Set-Up, Ramp-Up, Production, Unavailable, and Maintenance*. While a human resource can be composed of four modes; *Production*, *Learning*, *Maintenance*, and *Pause*

In that case, the resource allocation can be performed according to the current operating mode of each resource. For example, if both a human resource and a robot resource are in their production mode, we can consider that the robot resource is to be prioritised.

But, if the robot is in the unavailable mode (maintenance operations are needed), should the human operator be allocated to the production operations or should the human operator be allocated to the production operations or should the human operator be allocated to the maintenance operations first, and then the robot be allocated to the production operations?

5 LOGIC OPERATION PLANNER

To be able to perform both task and resource allocation in a more complex system there is a need for software. Sequence Planner (SP) is a prototype software tool developed to manage the Sequence Of Operations (SOP) language and to perform sequence planning [9] SP handles operations and permits to build Sequences of Operations according to pre- and post-conditions associated to each operation. These sequences of operations can be represented from different points of view. For example, SP can represent SOPs from a *product* point of view (sequences of operations related to one product) or from a *resource* point of view (sequences of operations performed by a specific resource).

To ease SOPs representation, several concepts have been introduced in order to express parallelism, alternatives, arbitrary order, etc. One important concept is the concept of hierarchy. A hierarchical relation can be used to represent in detail how an operation is performed. This hierarchical representation permits to simplify the representation of an SOP and only display information that are important for the end-users: either a high-level view of a whole system or a low-level view of a part of a system.

The Sequences of Operations (SOP) language [9] is a graphical language used to specify and visualise relations among operations. This SOP language is based on an operation model. Sequences of operations are defined with the help of pre- and post-conditions related to each operation. Figure 1 presents how an operation for a product can be represented using the SOP language.

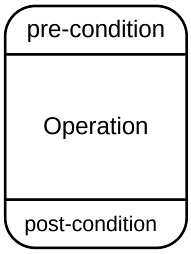

Figure 1: Representation of an operation using SOP language

Pre-conditions, and respectively post-conditions, of an operation can be composed of guards and actions. Those guards and actions are defined through variables. A guard is a condition that must be satisfied so that the operation can start (or finish). An action permits to define or change the value of variables when the operation starts (or finishes). For instance, a pre-condition related to the booking of a resource is both a guard and an action: the resource needs to be available (*R1==available*) and the resource is then booked (*R1=booked*). The pre-condition associated to the resource booking is (*R1==available* ∧ *R1=booked*). The fact that both guards and actions can be used in a same condition helps engineers in expressing functional needs.

As a conclusion, this SOP language is based on the fact that a sequence of operations should not be considered as a compulsory input data but as a consequence of relevant pre- and post-conditions on when and how the operations can be executed.

5.1 Example of resource allocation using Sequence planner

The example will show a local optimisation of resource allocation assembling a product illustrated in Figure 2. This example is a *Product* composed of two pieces: *Part A* and *Part B*, assembled together with seven *Rivets*.

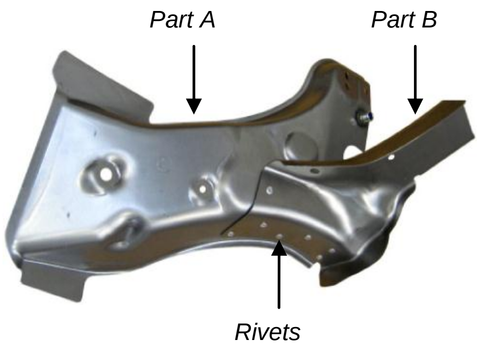

Figure 2 Two sheet metal parts A and B assembled with 7 rivets

This product is produced in a cell composed of three types of resources: two robots (R1 and R2), a fixture (R3) and two human operators (R4 and R5). These resources can perform different operations; their abilities can be redundant or not as will be detailed in the ranking matrix (Table 1). The following description briefly explains how the product is to be produced (also illustrated thru sequence planner in Figure 3):

First, *Part A* and *Part B* must be placed on the fixture. They can be placed either by a robot or a human operator.

Then, *Part A* and *Part B* are fixated on the fixture by clamps controlled by the fixture itself.

Then, *Part A* and *Part B* are assembled together with seven *Rivets*. This operation can also be performed either by a robot or a human operator.

Finally, the product is inspected. Depending on which resource performs the operations to place *Part A* and *Part B* and the assembly operation, the inspection operation differs.

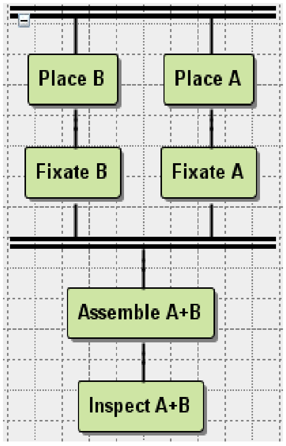

Figure 3: SOP generated according to the conditions on product requirements

In order to create route flexibility and to perform task and resource optimisation, input data from three parameters are defined:

- ***A set of operations*** i.e. operations that must be performed on the product (Figure 3). The order of the operation is then globally optimised, based on the pre-and post-conditions related to the product design.
- ***A set of resources (in this example; R1-R5)*** with detailed operations. For each resource, each operation that it can realise is detailed through a hierarchical relation. Figure 4 gives an example of detailed operation: detailed operation Place A for a human resource.
- ***A resource mapping***. This mapping permits to define and rank, for each operation, which resources are able to realise it, seen in Table 1 (main path is defined as 1).

The dynamic resource allocation is performed by adding pre-conditions related to resource booking. These pre-conditions force the assembly system to allocate the operation to one of the different resources.

First, all the alternative resource allocations are added to the SOP previously obtained according to the global optimisation. Then, pre-conditions are added to each first operations involved in the alternative resource allocations. These pre-conditions permit to define in which case the first resource should be chosen, in which case the second one should be chosen etc.

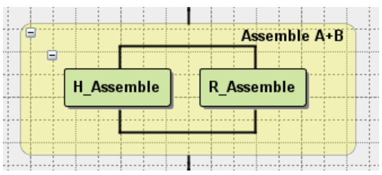

Figure 4: Resource allocation alternatives

The pre-conditions defining the selection of sequence among the alternatives can be defined using different criteria. Indeed, the best resource allocation is not always the same; two major features should be taken into account:

1. The resource allocation policy
2. The current "state" of each resource

The resource allocation can be based on a simplistic model such as available/unavailable resources. Such a model can be easily applied if we suppose that there is no resource breakdown, no maintenance task, etc. In that case, a resource could be allocated to an operation as soon as it is available. However, this simplistic model cannot be used to represent a realistic assembly systems, especially if this assembly system is composed of both human and robots resources. The "state" of each resource can be represented using operating modes [31]. For instance, a resource model can be composed of the five following modes: Set-Up, Ramp-Up, Production, Unavailable, and Maintenance. In that case, the resource allocation can be performed according to the current operating mode of each resource. For example, if both a human resource and a robot resource are in their production mode, we can consider that the robot resource is to be prioritised.

6 DISCUSSION

Is it possible to reach route flexibility and system proactivity through resource allocation and task optimisation?

An important factor in order to increase flexibility in system design is to plan the operation sequences (*in the specific software in this paper, tasks are defined as operations*) [39]. Methods that help the engineers to better understand operation sequences would therefore be an important contribution to their daily work. Especially methods that automatically identify and visualise the consequences of product and manufacturing design decisions on the operations would be useful [30].

In dynamic environments, local resource allocation is a possible solution i.e. activities of the operators' job are no longer fixed and the work situations he/she faces are unlikely to be identified solely by work instruction sheets[7].

7 CONCLUSION

The aim of the proposed resource modelling is to reduce the gap between a resource and its model, and to take into account human roles in early design phases of an automated system to avoid automation abuse [32].

It is possible if the tasks could be optimised at a global level but the resources performing the tasks will be allocated locally. Furthermore, in order to reach proactivity, dynamically changes in the system have to be possible.

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