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Modular simulation for line-less mobile assembly systems

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RESUMO

Dado o aumento na necessidade de produzir produtos customizados em lotes individuais, diferentes paradigmas de organização de produção tem sido investigados como uma alternativa a sistemas clássicos de montagem. Quando lidando com produção em massa, sistemas dedicados possuem diversas vantagens como menor tempo de processamento, custo reduzido e melhor eficiência. Entretanto, estes sistemas não foram desenvolvidos com o intuito de permitir a customização de produtos. Sua falta de flexibilidade a variações no produto resulta em custos elevados quando pequenos lotes de produtos customizados são produzidos. O conceito de Sistemas de Montagem móvel sem-linha (LMAS) é apresentado como uma solução para estes sistemas, adicionando mais um grau de liberdade para o conceito de reconfiguração de fábricas modernas. Em um LMAS, todas as entidades relevantes ao sistema são mobilizadas através do uso de veículos autônomos ao longo de todo o chão de fábrica. Assumindo um chão de fábrica livre de obstruções, recursos do sistema podem ser designados livremente e a organização de produção é determinada de acordo com o pedido a ser desenvolvido e os objetivos da empresa. Trabalhos anteriores desenvolveram diferentes abordagens ao problema de atribuição de tarefas e posicionamento de entidades. Entretanto, atualmente não existe uma plataforma de simulação adequada para validar o conceito de um LMAS. Este trabalho introduz uma plataforma de simulação modular para verificar este conceito e testar diferentes técnicas de planejamento e controle de produção. Um estudo de caso de LMAS é proposto, incluindo a seleção de recursos necessários para manipular e transportar partes e produtos através do chão de fábrica. Soluções para os problemas de representação de produto, controle de robôs e gerenciamento de frota no contexto de LMAS são propostas. A plataforma de simulação modular permite a simulação de diferentes configurações de chão de fábrica com um número variável de recursos. Testes então são realizados para validar a plataforma proposta. Resultados mostram que as soluções propostas podem ser integradas apropriadamente em uma plataforma que simula a montagem completa de um produto.

Palavras-chave: Simulação. Sistemas de montagem móvel sem-linha. Gerenciamento de frota. Sistema a eventos discretos.

ABSTRACT

With the increase in consumer needs of customized and lot size 1 products, research has progressed in finding alternative organizational production paradigms to classic Dedicated Assembly Systems. Although such systems present plenty of advantages such as faster processing time, improved efficiency and cost decrease when dealing with large lot sizes, these systems were not designed with product customization in mind. Their lack of flexibility results in higher costs when small, customized lots are produced. As an alternative to such systems, Lineless Mobile Assembly System (LMAS), add an additional degree of freedom to the concept of reconfigurability in modern factories. In LMAS, all relevant entities are mobilized by the utilization of autonomous guided vehicles within the factory. Assuming a clean floor approach, resources can be freely allocated on the shop floor and the assembly line is compiled based on actual jobs, orders and objectives. Previous work has developed distinct approaches to job scheduling and entities positioning. However, currently there's no suitable platform to validate the LMAS concept. This work presents a modular simulation platform to verify the feasibility the LMAS concept and test different production planning and control techniques. A LMAS case study is proposed, along with resources to manipulate and transport parts and products throughout the shop floor. Solutions to product representation, robot control and fleet management issues are presented. The modular simulation platform enables simulation of different shop floor configurations with a varying number of resources. Tests are then realized to validate the platform proposed. Results showed that the solutions proposed can be integrated properly into a platform that simulates the complete assembly of a product.

Keywords: Simulation. Line-less Mobile Assembly Systems. Fleet management. Discrete Event Systems.

LIST OF ABBREVIATIONS AND ACRONYMS

AGV	Automated Guided Vehicle
BOM	Bill of Materials
BOR	Bill of Resources
CNC	Computer Numeric Control
DAS	Dedicated Assembly System
FAS	Flexible Assembly System
KPI	Key Performance Indicator
LMAS	Line-less Mobile Assembly System
PPC	Production Planning and Control
RAS	Reconfigurable Assembly System

CONTENTS

1 INTRODUCTION

1.1 MOTIVATION

One of the most important processes in the value chain of production is assembly, where all the components are integrated to form the final product (HU et al., 2011). The end result, assembly, is a combination of design, engineering, manufacturing, and logistics, to create an object that performs a function.

Market trends nowadays show that costumer demands are shifting from standardized, mass-produced products to custom, highly personalized products. This presents a challenge to Dedicated Assembly System (DAS), as these were designed for more stable market environments. To achieve the necessary throughput, such systems take advantage of fixed transfer systems and fixed processes sequences. This, however, restricts modifications to the assembly line (HUETTEMANN; GAFFRY; SCHMITT, 2016).

Research has progressed in finding alternatives to DAS. Newly available technology has allowed for greater product customization while maintaining production costs and time reasonable. In this context, the concept of Line-less Mobile Assembly System (LMAS) is presented by WZL of RWTH Aachen as a solution for the assembly of large, customized products, offering additional flexibility to the assembly process (HÜTTEMANN; BUCKHORST; SCHMITT, 2019).

LMAS proposes that all of the components of the shop floor (e.g. workstations, tools and parts) are allowed to be reconfigured and reallocated dynamically in order to better comply with the company's goals, such as optimizing throughput or reducing manufacturing costs.

1.2 OBJECTIVES

Given the need of an environment to compare different production planning and control approaches, the present work proposes the utilization of a robotics simulation environment to perform such task. This platform should enable further investigation of logistics and low-level control issues not addressed in previous LMAS research. The simulation platform proposed should inform whether the assembly of a product can be executed or not, thus verifying the solution proposed by the production planner.

1.3 DISCLAIMER

Due to confidentiality reasons, some data originally contained in this report was omitted.

2 ASSEMBLY SYSTEMS

Investigation on different alternatives to traditional assembly systems started to gain traction at the end of the 20th century, following advancements of research on alternatives to traditional manufacturing systems (SCHOLZ-REITER; FREITAG, 2007).

The necessity to examine different organization and control policies for manufacturing systems arose during the 1980s with the increased availability of Computer Numeric Control (CNC) machines. These multi-purpose resources are capable of performing varying operations due to automatic tool changes and automatic handling of parts, and allowed an increase in shop floor flexibility to answer the needs for low-volume batches already present at that time (STECKE; SOLBERG, 1981).

Equivalent to manufacturing systems, assembly systems can also make use of the latest advancements on the robotics industry to handle the current turbulent market trends (JAIN; KOMMA, 2006). Although presenting low unit cost for the high-volume production of a single product, the benefits of DAS are lost when smaller batches are required as they are not designed with flexibility in mind, requiring reconfiguration time and costs when a new product needs to be assembled.

As an alternative to the classic systems Flexible Assembly System (FAS) were introduced. Such systems consist on a series of CNC assembly stations connected by an automated material handling system. This enables the assembly of a variety of product types in small to medium-size batches at a high rate (SAWIK, 1999).

Reconfigurable Assembly System (RAS) were later proposed based on the principle of reconfigurability, defined as "the ability to repeatedly change and rearrange components of a system in a cost-effective way" (SETCHI; LAGOS, 2004). RAS are composed by modular systems, either flexible or dedicated, enabling the assembly line to be expanded and its functionality and productivity changed according to demand (SEQUEIRA; BASSON, 2009). In contrast to FAS, RAS can adapt to new market demands by enabling changes on both the system level (e.g., adding machines) and the machine level (e.g., changing machine hardware and control software) after the system has been implemented (KOREN et al., 1999).

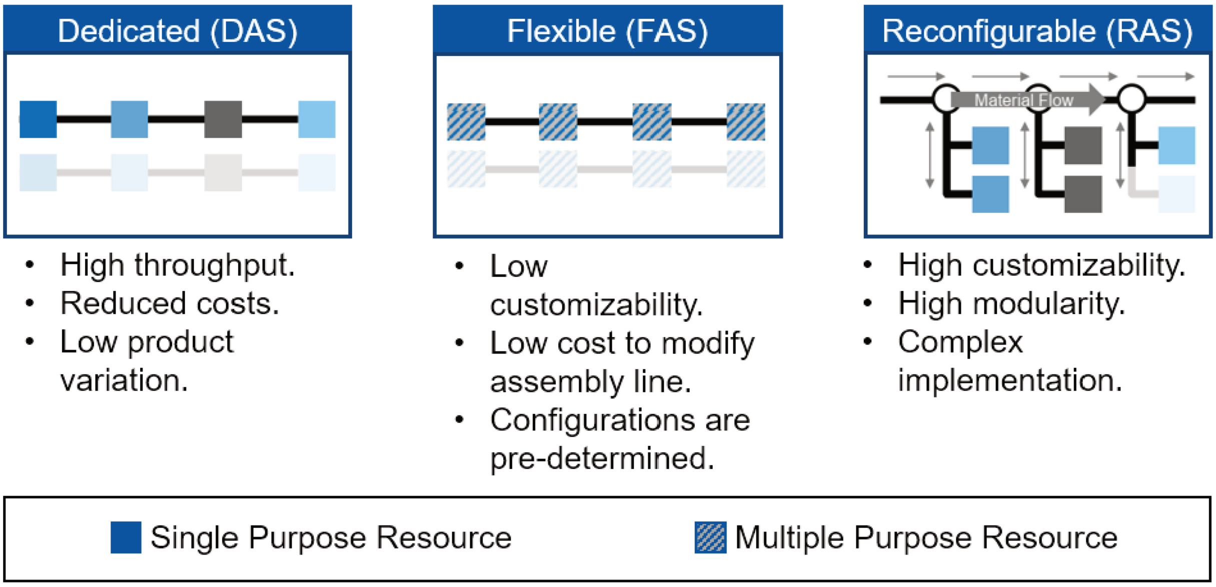
An overview comparing each of the assembly systems described is illustrated in Figure 1.

The concept of LMAS comes from the need to have a form of industrial assembly organization for large products. These products usually require great efforts to be manufactured and currently present temporal and spatial constraints that limit the possibilities for reconfiguration (HÜTTEMANN; BUCKHORST; SCHMITT, 2019).

To provide a solution for this issue, LMAS are founded on 3 main principles:

1. Clean floor approach,
2. Mobilization of all assembly relevant resources within the factory,

Figure 1 – Comparison between assembly systems.



Dedicated (DAS)

- High throughput.
- Reduced costs.
- Low product variation.

Flexible (FAS)

- Low customizability.
- Low cost to modify assembly line.
- Configurations are pre-determined.

Reconfigurable (RAS)

- High customizability.
- High modularity.
- Complex implementation.

Source – Buckhorst (2020), adapted.

3. Unrestricted assignment of resources and products to locations and resources to jobs.

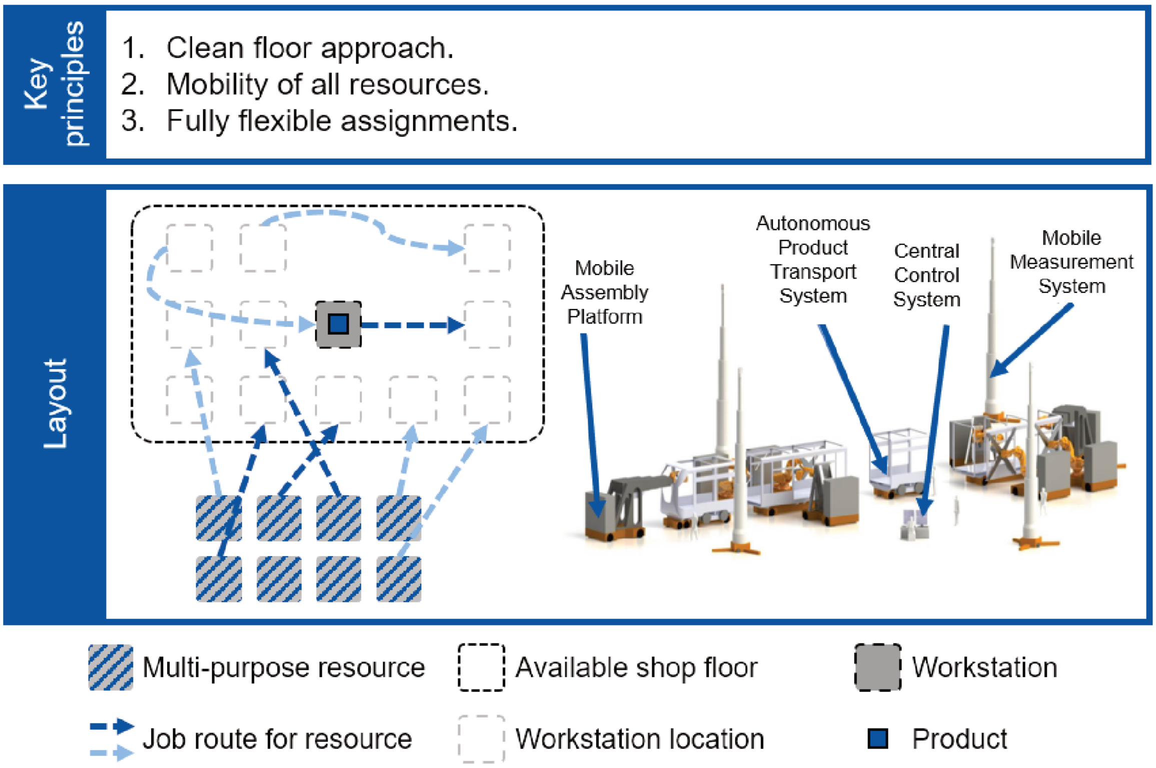
The clean floor approach is assumed to allow the resources to be moved around the shop floor with minimum spatial constraints. This way, it is desired that the operation area of a LMAS within the factory contains only the essential fixed infrastructure such as storage areas, fixed machinery, and support columns, thus maximizing the potential for reconfiguration. Different areas can then be arranged for specific purposes during assignment planning.

The principle of resource mobilization assures that the shop floor area can be utilized by the entities associated with the assembly process. Entities are any of the resources associated to the assembly itself, both parts and machines, transport systems and metrology systems. The product to be assembled must take into consideration the concepts of design for assembly (VAN BRUSSEL, 1990), being designed in a way that they can be handled by a resource with moving capabilities. Moving capabilities are granted to resources through mobile robots present in the shop floor like an Automated Guided Vehicle (AGV). Constraints like information, media and energy supplies that could eventually restrict the movement of resources must also be taken care of before deployment.

The last principle gives these systems the ability to attribute tasks to different resources. A job, or the order to assemble a product, is composed by several tasks, each of these being characterized as the set of actions taken by the resources to assemble a set of parts of a product. These tasks can then be assigned to any of the available areas of the shop floor, attaining the greatest flexibility possible within the usable shop floor (HÜTTEMANN; BUCKHORST; SCHMITT, 2019). The assignment problem can then be solved through an optimizer taking into consideration different metrics (e.g. minimization of lead time, minimization of production costs, maximization of utilization). Metrics are then to be chosen by the management level according to their needs.

Due to the high effort needed to transport big parts, the benefits of LMAS are more visible. The more difficult or costly it is to transport a part, the better it is to move resources around such part. An overview for LMAS is illustrated in Figure 2.

Figure 2 – LMAS principle.



Source – Hüttemann, Buckhorst, and Schmitt (2019), adapted.

When considering an assembly line whose transportation system has been dissolved from rigid links to a flexible system where transport can happen to different working stations as needed, the need for linearity in the assembly process is lost. With this proposal, an operation can happen with certain resources in parallel to others occurring into different locations with different parts.

Although the possibility of assigning an operation to distinct stations adds flexibility to the system, it also adds another layer of complexity to the overall assembly planning. A single product now can not only be assembled in different combinations of operations over the assembly time, but also in different combinations of operations and locations.

Due to the specifics of each assembly operation, different resources will need to be associated together to accomplish a given operation. Each set of resources to perform this operation then compose what LMAS defines as a workstation configuration. Operation planning then becomes a problem of assigning specific resources to given stations to perform the necessary tasks. Then, it assigns these stations to locations available on the shop floor at the time of the execution of the task.

While planning for such systems is envisioned to happen on a medium time scale (per shift), it must also take into consideration possible disturbances on the shop floor (e.g. faulty resources or broken tools) on a short scale as they happen. The flexibility allowed through the mobilization of all entities on the shop floor enable tasks to be reassigned at execution time and counter such disturbances.

3 FEASIBILITY SIMULATION

The realization of a LMAS system requires solutions to issues related to both shop floor organization and operation assignment not faced in conventional assembly systems. Proposing and verifying the solution to these problems is a process composed by a series of steps that must be followed in order.

The first step to conceive a LMAS is to define a case study that fits the project requirements and facilitates the observation of the benefits of such systems. According to the LMAS proposal, such systems focus on lot size 1 production of large-scale products (HÜTTEMANN; BUCKHORST; SCHMITT, 2019).

As with the assembly planning of every product, it is necessary to determine the details surrounding the assembly of a product. The Bill of Materials (BOM) of the product must be defined, detailing the number of parts necessary for its production. This list is based on the assembly bill, which determines how many units of each product are to be produced. An example of the BOM is shown in Table 1.

Table 1 – BOM for a product.

Identifier	**Quantity**
PART 1	1
PART 2	2
PART 3	1
PART 4	1
PART 5	4
PART 6	1
PART 7	4

Source – Author (2019).

Based on the BOM for the product selected, a set of operations to perform the assembly of the product is defined. Each operation is a task performed into one or more parts, in order to achieve proper assembly. Operations may require previous operations to be performed, also called precedence operations, due to physical constraints of the product. Table 2 illustrates the list of operations for a product and details their precedences.

From the list of operations considered for the assembly of a product, a precedence graph can be derived, thus illustrating the order of the operations to be performed. This is illustrated in Figure 3.

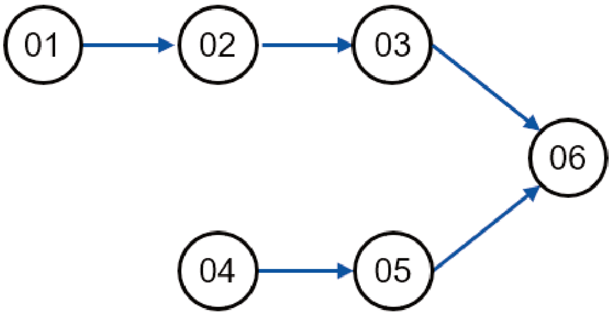
Being the central point of the assembly, the product design dictates the choices for all other entities on the assembly system. The assembly operations to build a product dictates the types of resources necessary, as they need to be capable of performing such tasks. Also, the more parts and operations the product has, the more resources will be needed to both assemble and transport these between stations. Similarly to the

Table 2 – Operations and prerequisites for the assembly of a product.

Identifier	**Operation**	**Precedence**
OP 1	Part 2 to Part 1	-
OP 2	Part 3 to Part 2	OP 1
OP 3	Part 4 to Part 3	OP 2
OP 4	Part 6 to Part 5	-
OP 5	Part 7 to Part 6	OP 4
OP 6	Part 5 to Part 4	OP 3, OP 5

Source – Author (2020).

Figure 3 – Sample Precedence Graph.



Source – Author (2020).

BOM, the Bill of Resources (BOR) is introduced to state the amount of resources of each type necessary for the assembly.

Another factor is the shop floor environment. Although LMAS considers a clean-floor approach, in practice this may not be possible. Depending on shop floor limitations, changes to assembly planning are necessary. For this reason, details regarding shop floor size, how the resources can be distributed along its space and restrictions to assignments must be reviewed. Restrictions can be any obstacles, charging stations or cabling access points required and even specific positions for loading and unloading of parts and products.

The combination of both the BOM, the BOR and the shop floor state defines the scenario to be studied. This set of information is then supplied to the production planning entities and the simulation platform to obtain consisting results through all analysis made.

Given the inherent flexibility achieved with a LMAS implementation, Production Planning and Control (PPC) becomes a challenging task. With unrestricted assignment of resources, operations and locations, there are many variables to the question of finding an optimal solution to a given objective.

One research need related to LMAS is the development of an optimization methodology that enables flexibility on assignment of locations. The methodology must compute a solution with minimal cost and/or time for production. Here, workstation configuration, operation scheduling and transport planning are also to be considered. This optimizer output is the production plan, containing the position and time at which each operation should be performed, along with the resources to execute it.

Another need of research is the short-term control of resources. As with any production system, resource failures are always a possibility. The reconfigurability enabled by LMAS enables production control to act on these issues during production. Workstations can have their resources replaced. Operations can be performed in idle assembly stations when needed. Transports can plan for obstructed paths on the shop floor. A proper control system can then minimize the effects of disturbances and prevent production from being halted.

To make production coordination possible, proper data organization and communication between LMAS entities is also required. Data models need to be elaborated to keep track of shop floor, resources and assemblies during planning and production. A communication layer between resources and the control system must be studied. Lastly, details regarding the physical interactions regarding parts delivery to stations and their handling by resources are to be investigated.

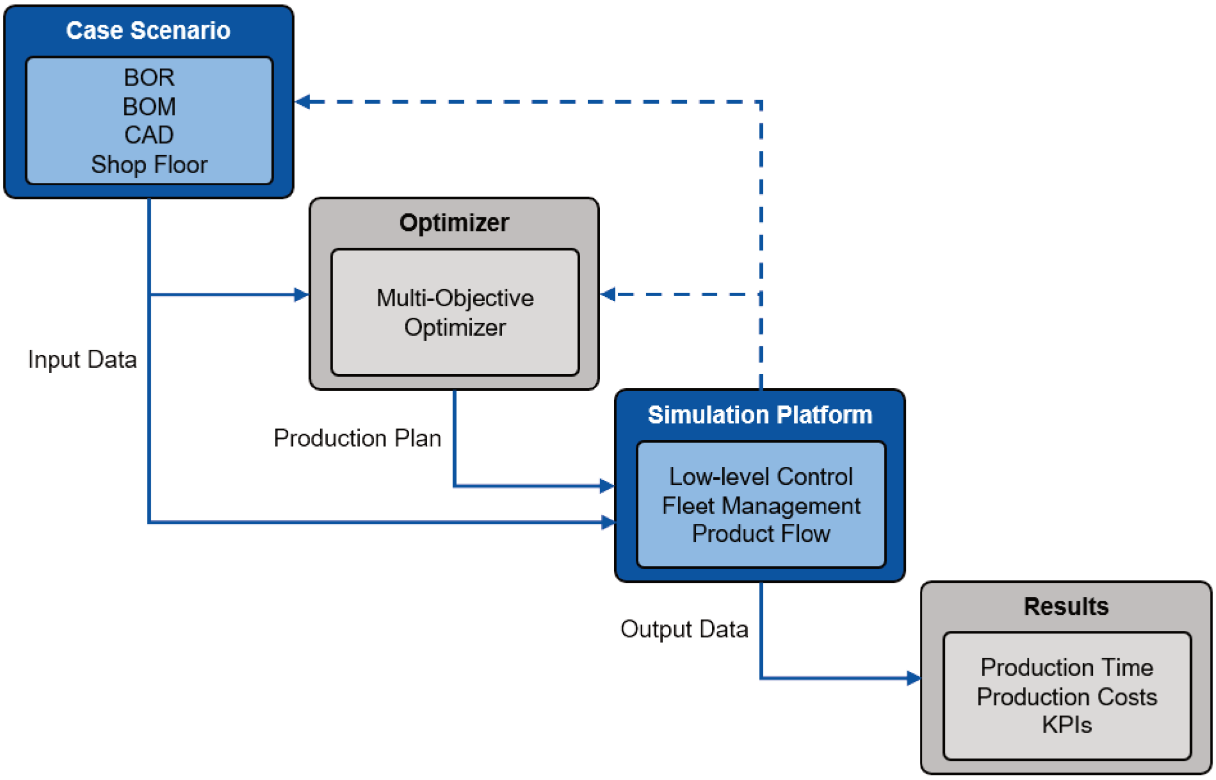
No work previously developed presents solutions for the underlying issues related to the low-level robot control, parts handling and transport management issues that are present in an operable implementation. For this reason, a modular simulation platform is proposed to fill this gap. With the simulation results, modifications can be proposed to both case scenario and optimizer in an iterative manner to improve results. An overview of the LMAS context, highlighting the activities performed during this work, is presented in Figure 4.

It is not a requirement for the simulation platform proposed in this work to compute the solution for the PPC problems. The platform assumes optimization data is previously computed and provided as an input to the platform along with the scenario definition.

After the simulation scenario is loaded based on the input data, the platform must execute the production plan provided by the optimizer software. The plan describes the shop floor status at each time step during execution and which operation should be performed at the assembly stations. An example for the production schedule is shown in Table 3, indicating the operations to be executed, the workstation where each operation is to be performed and the resource responsible for performing it.

A successfully implemented simulation platform should provide solutions to all of the issues described above. This way, the complete production plan can be simulated. The platform should then supply the user with the Key Performance Indicator (KPI)s associated with the scenario analyzed, such as total time and cost of production. Given the different nature of LMAS, additional indicators can be considered diffently than in conventional assembly lines. HÜTTEMANN AND BUCKHORST proposed specific KPIs

Figure 4 – Iterative workflow for LMAS research.



Source – Author (2020).

Table 3 – Assembly schedule.

Operation Number	Location	Resource
OP 1	WS1	RES 1
OP 2	WS1	RES 2
OP 3	WS2	RES 2
OP 5	WS2	RES 1
OP 6	WS1	RES 2

Source – Author (2020).

to LMAS such as total system scalability, number of station reconfigurations, position changes in factory configuration and overall distance travelled by resources that are more adequate to evaluate such systems (HÜTTEMANN; BUCKHORST; SCHMITT, 2019).

By simulation of optimizer results, schedules, resource routes and low-level control of resources can be validated. Suitable solutions can then be implemented as desired.

4 METHODOLOGY

Shop floors in reality hold a great number of machines of different types, each operating with different tools and specific requirements such as consumables or human operators. Different metrology systems need to be present to gather information from the processes to the management sector of the company for PPC purposes. Varying environment setups may also be required depending on the configurations needed to produce a certain product.

Although each of these characteristics are important in-site, developing a simulation model that takes into consideration all these aspects would imply great costs. One of these costs is the computational requirements regarding the amount of information to be processed. In addition, the time and human resources required to get each of the components described properly simulated and integrated into one single application increases with the amount of detail desired.

For this reason, it is important to define the scope of the process analyzed on this work and focus on the details that are relevant to LMAS simulation.

In this work, simplifications to the assembly of the product considered and its representation, the grasping of parts and products, the shop floor logistics and the metrology system are made, enabling development under the time-frame of the project.

A bottom-up methodology was deployed in this work (BUEDE; MILLER, 2016). Starting with the product to be assembled, all product data necessary to the assembly process needed to be collected. From this, robot control was implemented to verify assembly feasibility based on product data. Then, a transport control layer was implemented, allowing resources movement on the shop floor. Lastly, integration from the bottom layers was performed to achieve a complete LMAS simulation.

To enable the platform to perform the assembly of the product, a representation for the product is proposed, containing the most important characteristics to be considered during the assembly process. This metadata, along with other files describing the physical characteristics of each part are introduced to the simulator for its assembly to be simulated. During the execution of the simulation, values for the combinations of parts are also computed, enabling the platform to keep track of all subsets of parts until the full assembly is achieved.

In addition, a model for the shop floor is proposed, enabling the platform to allocate resources on the shop floor and modify these assignments over time, according to the production plan. The shop floor is modeled as a space where workstations can be assigned to, each in a specific location. Each location is then divided into smaller units named cells, which can have a resource assigned to it. This enables the platform to manage the resources scattered through the shop floor and plan movements of resources accordingly.

A controller to coordinate navigation of the movable entities through the shop is also introduced. When a request for a resource is made to this controller, a new route is computed, from the resource's initial to final position. The computation for this route takes into consideration routes previously assigned to other resources, in order to prevent collisions. A heuristic is deployed to solve the graph-traversing problem when computing routes, aiming to achieve the best collision-free route possible. For this, characteristics of the movements performed by the resource are modeled, and a cost-function is obtained. The movement restrictions for the shop floor are also considered. When a route is possible, the controller sends to the resource the route to be performed by the resource, which is then executed. At completion, the resource signals to the main controller that its destination was achieved, enabling additional routes to be computed and executed by other resources.

Robotic manipulators are then required to operate and execute the assembly. When properly supplied with the necessary parts for the assembly, the controller for the robots requests a set of operations to the robots of the workstation where the operation is to be performed, enabling cooperation of the robots to successfully join the parts associated with that operation. Each operation to be performed is broken down into sets of pick and place operations, depending on the current characteristics of the part or sub-assembly to be manipulated.

In order to achieve the necessary control for the manipulator, each of the possible assembly situations was studied, listing the possible scenarios that could result in singularity configurations. Solutions are provided to enable robot operation while avoiding these configurations: Outer workspace singularities are avoided by always supplying the parts to the robot within its workspace. Inner workspace singularities are solved by creating alternative, safe paths to routes that could initially result in a singularity.

After validating each of these components, a full assembly of the product was to be achieved. For the assembly to be performed, a sequence is followed by the main controller of the simulation: First, the operations are read by the main controller of the simulation. Then, requests are sent for each of the resources to perform the operations described in the production plan, including retrieval of parts from specified storage areas on the shop floor, transport of parts to workstations, execution of assembly operations by the workstations, and delivery of the product to the final logistics area. At each iteration of the simulation, the simulator informs the main controller about the status of the shop floor and the assembly, enabling proper planning for execution of the following operations. When an operation is successfully executed, the main controller executes the next operation on the plan, until the full production plan has been executed.

5 CONCLUSION

The concept of LMAS arose from current needs of the industry: To provide greater product customization while maintaining production costs and time at a reasonable low level. Usage perspectives, requirements, roles, assessment methods and optimization models have already been proposed in previous work. However, no solution had been proposed to open questions such as the control of LMAS entities and the coordinated execution of PPC techniques.

Given this background, this work aimed at resolving this research gap. The main goal was to develop a modular simulation environment for simulation of PPC techniques applied to an LMAS use case.

In order to develop a modular simulation platform for a LMAS, first a product to be assembled was defined. A mobile robotic manipulator was chosen to perform the assembly of the products, given the mobility requirement of LMAS. An AGV model was also selected, serving as the transport system to move parts across the shop floor. The product, along with the manipulator and the automated vehicles, define the case study scenario of this work.

To provide the control system with the physical description of the product, a representation of the product was proposed, thus enabling the assembly operations to be performed. The representation proposed allowed the system to determine how parts should be placed in relation to each other and with this, full assembly of the product to be achieved.

For operations to be performed, a control logic was proposed for the robotic manipulators. The objective of the logic implemented was to prevent singularity situations from happening while the manipulator handled a part. Solutions were presented to each of the possible singularity situations that occur for the manipulator chosen. This enabled the full assembly of the product to be performed.

With the necessity to move entities across the shop floor, a shop floor representation was introduced. Then, a controller was proposed to manage the movable resources across the shop floor. The controller implemented enabled collision-free navigation for multiple vehicles at the same time, thus satisfying the requirement of resource mobility.

Platform modularity was achieved by allowing the user to define the amount of resources of each type to be simulated, along with additional parameters to proper represent the resources into the simulation platform.

In summary, the objectives proposed in this work were achieved. With the complete assembly of the product being successfully simulated, it is possible to affirm that a modular simulation environment can be deployed to verify the feasibility of a LMAS case study and provide a foundation for further research on LMAS implementation and the underlying logistics and control issues.

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