Digital twin framework for reconfigurable manufacturing systems (RMSs): design and simulation

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Abstract
Faced with the global crisis of COVID-19 and the strong increase in customer demands, competition is becoming more intense between companies, on the one hand, and supply chains on the other. This competition has led to the development of new strategies to manage demand and increase market share. Among these strategies are the growing interest in sustainable manufacturing and the need for customizable products that create an increasingly complex manufacturing environment. Sustainable manufacturing and the need for customizable products create an environment of increased competition and constant change. Indeed, companies are trying to establish more flexible and agile manufacturing systems through several systems of reconfiguration. Reconfiguration contributes to an extension of the manufacturing system’s life cycle by modifying its physical, organizational and IT characteristics according to the changing market conditions. Due to the rapid development of new information technology (such as IoT, Big Data analytics, cyber-physical systems, cloud computing and artificial intelligence), digital twins have become intensively used in smart manufacturing. This paper proposes a digital twin design and simulation model for reconfigurable manufacturing systems (RMSs).

Keywords
Reconfigurable manufacturing system (RMS) · Modular framework · Generic model · Digital twin (DT) · SysML

1 Introduction
Faced with a global COVID-19 crisis, manufacturing companies have become aware that they must react quickly to sudden changes in the market to remain competitive. The increasingly competitive nature of companies therefore depends on their ability to react quickly and at the lowest cost to market fluctuations in the supply and demand context [1]. The ability to reconfigure a manufacturing system makes it possible to change its production rate and product type with a minimum of cost and time. It is achieved by integrating new resources (transport or processing) into the production system but also by adding new components (human, hardware and software elements) [2]. In the literature, a reconfigurable manufacturing system is derived from modular basic processes, both software and hardware, that can be rearranged or replaced quickly and easily. To achieve the correct structure, good management practices, ranging from design to construction, are required, according to [3]. Reconfigurability allows the production line to be improved and upgraded rather than replaced as needed [4]. According to Wiendahl and Heger [5], reconfigurability is the practical ability of a manufacturing or assembly system to switch reactively and rapidly the production mode of a number of units or sub-assemblies through the addition or deletion of isolated functional elements. Ultimately, the target is to provide the precise functionality or production capabilities required at the desired time. The reconfiguration phase of manufacturing systems, when an established system is restructured, requires adaptability [6].

Industry 4.0 has been actively researching this area for almost a decade. It is currently a top priority for many companies [7]. Technology contributes to the prediction of
upcoming market trends and customer needs and to real-time decision making and the design of reconfigurable manufacturing systems (RMSs). With Industry 4.0, manufacturing operations can integrate insights gained from the use of advanced technologies such as the Internet of Things (IoT), data analytics, modeling and simulation, and optimization to respond in real time to changes in raw material costs, custom orders, inventory levels, etc. Grieves and Vickers [8] introduced in the 2000s the concept of DT for product lifecycle management. It consists of three main parts: the physical product in real space, the virtual product in virtual space and the bi-directional data and information connections, which link the two spaces. Later, Glaessgen and Stargel [9] defined DT as “an integrated product lifecycle management system” that is multiphysical, multiscale and probabilistic of an as-built vehicle or system that uses the best available physical models, sensor updates, fleet history, etc., to replicate the life of its corresponding flying twin. In 2014, Grieves [10] defined DT as: a set of virtual information constructs that fully describe a potential or actual physical manufactured product, from the micro-atomic to the object level. Subsequently, the concept of DT has been extended from the product to the manufacturing system as a whole [11, 12]. A digital twin is a digital representation of a physical item and is created using IoT and sensor data. It monitors physical operations, controls the physical elements, tests what-if scenarios, predicts the future behavior of the physical elements and supports decision making [13]. Recently, an ISO 23247 standard, Digital Twin Framework for Manufacturing has been introduced. It defines a framework that provides guidelines, reference architecture, methods and approaches for case-specific digital twin implementations [13]. Despite the growing popularity of Industry 4.0 and research into digital twins and the various frameworks introduced to integrate them into the manufacturing environment, little research has considered its incorporation into RMS.

The aim of this paper is to propose an approach to design and simulate a reconfigurable manufacturing system using digital twins, which should allow the deployment of different configurations. As an emerging technology, the digital twin (DT) aims to create a digital representation that reflects the functionality, structure and performance of a physical entity. The overall goal of the digital twin is to track the physical assembly line with a mirrored digital copy and to adjust and control the physical assembly line via a background analysis and decision model. This is relevant because companies need practical guidance on the order and manner of design implementation to better leverage reconfigurability in their businesses. In addition, it provides powerful support for modeling and simulating virtual manufacturing system configurations to make digital twins universal in the manufacturing industry, this helps solve specific problems in each important phase of manufacturing.

The rest of the paper is organized as follows: Sect. 2 describes the existing approaches through a literature review. In Sect. 3, we present our model with a formalization and a representation for each component of the model. High-level meta-models for structure, operations and configuration will be presented using the SysML modeling language. Finally, an implementation of reconfiguration scenarios through a digital twin simulation will be presented. Finally, the section concludes this study with a perspective.

2 Literature review

In this section, a literature review has been prepared. This includes different types of work; we have brought together all the papers dealing with this subject in order to study the existing situation. We proceeded by classifying the papers according to the criterion of the proposal which resulted in two groups: papers proposing design approaches and papers proposing digital twin approaches for intelligent manufacturing systems or for RMS.

2.1 Design approaches

According to Koren and Shpitalni [14], RMS should be designed according to the principles of reconfiguration. The more applicable these principles are to a manufacturing system, the more reconfigurable that system is. The implementation of these principles in the design of RMS leads to the ultimate goal of creating a dynamic factory that can quickly adapt its production capacity while maintaining high levels of product quality. These principles are:

- An RMS must provide adjustable production resources to respond to unpredictable market changes and intrinsic system events.
- An RMS must be designed around a product family, with just enough customized flexibility to produce all members of the family.
- The basic features of an RMS should be built into the system as a whole, as well as into its components (physical and logical).
- The capacity of an RMS must be able to be adjusted quickly (incremented or decremented) in small increments.
- The functionality of an RMS must be able to be quickly adapted to new products.
- The built-in adjustment capabilities of an RMS should facilitate a rapid response to unexpected equipment failures.

In the context of RMS design, Bruccoleri et al. [15] proposed a simulation to show the advantage of reconfiguration
to cope with contingencies and errors, of which they suggested an object-oriented structure for reconfiguration control.

Deif and ElMaraghy [16] have suggested an approach for the design of a reconfigurable production system. The proposed architecture takes into consideration the different design activities from the request to the final design of the configuration which provides performance measures that are used to control the design process.

The architecture consists of two modules:

- The first module describes the design process of reconfigurable manufacturing systems;
- The second module describes the process control for each level.

It has been applied on three levels:

- The market;
- System reconfiguration;
- Component reconfiguration.

As part of the work of Pascal Berruet and his team, the Lab-STICC introduced a representation language, called DeSyRe meaning Description of Reconfigurable Systems [17]. Lamotte proposed an approach which consists in dividing the description of the RMS according to two axes. The first axis, horizontal, separates the architecture of the system from its configurations. The second vertical axis of decomposition of the system is the logical/physical axis. This axis separates the “product” aspects constituting the logical part of the system, from the “machine” and “transport” aspects belonging to the physical part. In his approach, Chalfoun [18] changed the term architecture into the term structure. He also defined two types of configurations which are a physical (hardware) configuration of each workstation (for example, a workstation, conveyors, robots), control software and logical (software) configuration: assignment of a control program. To properly organize this RAMS model, Chalfoun has placed the structure in a “Structure” package. This package is broken down into two other packages: “Physical Structure” and “Logical Structure” which, respectively, contain the representations of the physical structure and the logical structure. In addition, operations play a central role in this organization. Each element of this model was then formalized and represented in modular “block” components. The approach proposed in Rösiö [6] is based on a conventional system design. As a starting point it takes method of developing manufacturing systems which includes initiation, preparatory design and detailed design. In addition to this, the support for considering reconfigurability is incorporated. An essential part of this support is how to determine the need for reconfigurability in the system and the link between these needs and the generic characteristics of RMS. In her design, she defined the production system reconfigurable in three parts:

- The logical reconfiguration concerns the modifications linked to the information system which manages the operating mode of the system. It can be a reprogramming of robots and automated tools or re-planning of manufacturing flows.
- Physical reconfiguration concerns the technical systems of each manufacturing system and the handling between these production units.
- Human reconfiguration concerns the reallocation of operators or robots to different workstations.

Koren et al. [19] formulated the design and operating principles of RMS and provided a review of the state of the art of design methods and methodologies for designing and operating RMS according to these principles. Subsequently, they proposed future research directions and discussed how recent smart manufacturing technologies can advance the design and operation of RMS. Youssef and ElMaraghy [20] developed an optimization program that determines the system configuration, the type of machines and the operations assigned to each stage. Goyal et al [22] constructed algorithms to select the optimal RMS configuration based on the reconfigurability and operational capacity of the RMT. Benkamoun et al. [24] reviewed the main strategies dealing with product variety and change in the design of assembly systems. Renzi et al. [24] reviewed the state of the art on the design of cellular RMS, compared to DMS, through optimization. They focused on meta-heuristic methods and artificial intelligence, since these have been shown to be effective and robust in solving complex manufacturing design problems. Hashemi-Petroodi et al. [25] developed in his paper several promising research directions in workforce reconfiguration planning, namely the use of machine and workforce reconfigurations, the consideration of ergonomic aspects, the combination of several workforce reconfiguration strategies, the study of workforce reconfiguration in human–robot collaborative systems and the use of new technologies in industrial human–machine environments.

RMSs are complex systems and reconfigurability brings more complexity, this makes their design more complicated than conventional manufacturing systems. Previous research indicates that design methods for conventional manufacturing systems cannot support the design of RMS, as, mainly, they do not take into account the requirements of reconfigurability [6]. Many authors indicate that a systematic design method for RMS is missing [26, 27]. For example, Bi et al. [26] present a review of existing methods for the design of
the system architecture, its configuration and the design of its control system. They conclude that a systematic design method is missing. Furthermore, in the current research, the successful implementation of RMS has not yet been widely reported. Some researchers have investigated the attitudes and barriers of reconfigurability in industry and concluded that various misconceptions and a general lack of understanding of reconfigurability are present [6, 28] and that various critical barriers to its implementation exist [29]. According to Rösiö [6], there is a focus on methods and techniques to achieve reconfigurability, but a general and comprehensive perspective on reconfigurability is rarely given. Therefore, the importance of developing a systematic design method for an RMS should be emphasized, as it provides the necessary knowledge on how to develop and realize the benefits of reconfigurability.

2.1.1 Digital twin approaches

The Industry 4.0 paradigm requires the modeling of manufacturing and other systems via the concept of the virtual factory and the use of advanced (cognitive) artificial intelligence for process control, which includes autonomous adjustment to operating systems (self-organization). The new modeling and simulation paradigm that is best suited is the digital twin concept. The digital twin concept extends the use of simulation modeling to all phases of the product’s life cycle, where products are first developed and tested in detail in a virtual environment [30]. Grieves [10] defined the digital twin as a set of virtual information constructs that fully describes a potential or actual physical manufactured product, from the micro-atomic to the macro-geometric level. In its optimal form, any information that could be obtained by inspection of a physical manufactured product can be extracted from its digital twin. Today, in the design of manufacturing systems, the most important attributes are flexibility, responsiveness, cost-effectiveness and the ability to be easily reconfigurable. In this context, Zhang et al. [31] developed a digital twin-based reconfigurable modeling approach to enable automatic reconfiguration of the digital twin-based manufacturing system. The authors proposed a reconfigurable digital twin system framework driven by a five-dimensional model. Furthermore, by mapping physical and virtual entities, they can deduce some of the capabilities and dependencies of the digital twin. In addition, the researchers used an extensible model structure and optimization algorithms to propose a reconfigurable strategy. The aim of their study was to meet the requirements of different granularities and targets in terms of reconfigurability. In the same context, Benderbal et al. [32] provided a conceptual modular RMS-DT framework as a way to integrate the digital twin into the RMS. In fact, the digital twin framework aims at providing a holistic system visibility and a flexible decision-making process to achieve the necessary responsiveness of the reconfigurable manufacturing system and improve its performance during its operation phase by continuously collecting real-time data from its components. Then, these data can be stored, processed and analyzed using information analysis as well as simulation and optimization module blocks. Based on the above ideas, digital twins can quickly provide critical decisions, such as the appropriate configuration of the reconfigurable manufacturing system, in order to effectively deal with sudden changes in a globally competitive market.

According to Xu et al. [33], in their special issue on Smart and resilient manufacturing in the wake of COVID-19. The authors focused on the technical aspects of a manufacturing system or rather technology solutions that can help cope with the pandemic as we know it today and make them agile and resilient in case of a similar event.

According Zhang et al. [34] in their paper on “Resilience dynamics modeling and control for a reconfigurable electronic assembly line under spatio-temporal disruptions”, he proposed a resilience dynamics modeling and control approach for a reconfigurable electronic assembly line under disruptions. A digital twin (DT) platform is developed as a basis for resilience analysis, and open reconfigurable architectures (ORA) are introduced to support the reconfiguration of the assembly line.

Shao and Helu [35] in their paper “Framework for a digital twin in manufacturing: Scope and requirements,” the authors synthesized different perspectives on the digital twin to guide the development of a standardized framework that allows manufacturers to develop digital twins for specific purposes more easily, cheaply and quickly. A recently developed International Organization for Standardization (ISO)/Draft International Standard (DIS), ISO 23247, Digital Twin Manufacturing Framework, is one such standard. This standard defines a framework that provides a generic guideline, reference architecture, methods and approaches for case-specific digital twin implementations. The standard supports model composability and interoperability between modules. It also provides examples of data collection, communication, integration, modeling and implementation of relevant standards [13].

In terms of reconfiguration, Leng et al. [36] proposed a new approach based on digital twins for a fast reconfiguration of automated manufacturing systems and a fast optimization process. The digital twin consists of two parts: the semi-physical simulation that maps the system data and provides input data to the second part, which is the optimization. The results of the optimization part are sent back to the semi-physical simulation for verification. The proposed approach allows for rapid changes in manufacturing system capacity and the rapid integration of multiple processes into existing systems, enabling manufacturers...
to quickly launch new product orders. Related research and the application of the digital twin to product lifecycle management were presented in the papers by [37]. Zheng et al. [7] presented a broad and narrow definition of the concept and characteristics of digital twins. Based on the mentioned definitions, the authors introduced a digital twin framework for product life cycle management. This framework includes an information processing layer with three main functional modules, namely data storage, data processing and data mapping. As we can see from the literature review and to the best of our knowledge, there is a lack of research work around holistic and unified digital twin frameworks that integrate the design and modeling of the reconfigurable manufacturing system as well as the software reconfiguration. In this context, the objective of this paper is to try to find a complete method from design to simulation of the reconfigurable manufacturing system. It will be adapted by digital twin users according to their needs. In this paper the Reconfigurable Manufacturing Systems - Digital Twin (RMS-DT) framework will deal with several aspects of the different production lines which usually represent complex and heterogeneous areas. Therefore, a modular aspect has been implemented. In addition, the conceptual elements implemented in the digital twin are physically linked to their counterparts to ensure bi-directional communication between all parts of the digital twin.

- Management information systems, such as the Manufacturing Execution System (MES) and Enterprise Resource Planning (ERP) system, can help a company become more self-aware by linking business areas, using a single source of information and producing accurate real-time reports.
- The human–machine interface is used to ensure the best interaction between the physical and virtual parts of the digital twin. This interface is typically used to achieve intelligent, data-driven decision making in the intelligent manufacturing environment.
- The main objective of an RMS manufacturing system is to ensure responsiveness with customized flexibility. It is therefore necessary to consider the coupling of manufacturing system flexibility with scalability and modularity. This coupling must also be considered in RMS-DT frameworks.

This paper proposes a structured and integrated RMS-DT framework that evaluates the sustainability performance of the whole manufacturing system and ensures the reconfiguration of the hardware and software part to provide a flexible decision process (Table 1).

### 3 Proposed approach

The methodology of this work is to contribute to the implementation of the modeling of RMS and a methodology for their design, deployment and operation. We propose the integration of various reusable components in order to achieve the reconfigurability and flexibility of a manufacturing system and to respond to the various requirements imposed (launch of a new product/ failure / breakdown of a workstation). The supervision and control of the system must be built in such a way as to be able to support the reconfiguration capabilities of the system. We recommend an approach based on the concepts of systems engineering which allows us to characterize the reconfiguration needs and then to transform them into requirements. This would provide guidance through all the aspects of design, construction and operation of the system. Some performance indicators require the simulation of the real behavior of the production system, such as capacity utilization, reliability and flexibility. Simulation is even more important in the context of reconfigurable manufacturing systems design, where hazards vary from one product to another. Digital twin simulation is an effective way to analyze changes in the internal variables of the manufacturing system and improve its performance. To improve their performance, companies need to carry out continuous evaluation in all parts of their process. Hence the need to simulate the design of the system for the evaluation and improvement of its performance. We will base this work on the ISO 23247 standards, Digital Twin Manufacturing Framework, specifically the use case

| References                          | RMS-Design | RMS-DT |
|-------------------------------------|------------|--------|
| Yang and Li [37]                    | ✓          |        |
| Deif and ElMaraghy [16]             | ✓          | ✓      |
| Bruccoleri et al. [15]              | ✓          |        |
| Koren and Shpitalni [14]            | ✓          |        |
| Grieves [10]                       | ✓          |        |
| Chalfoun [18]                      | ✓          |        |
| Zheng et al. [7]                    | ✓          | ✓      |
| Zhang et al. [31]                   | ✓          | ✓      |
| Benderbal et al. [32]               | ✓          |        |
| Leng et al. [36]                    | ✓          | ✓      |
| Koren et al. [19]                   | ✓          | ✓      |
| Youssef and ElMaraghy [20]          | ✓          |        |
| Dou et al. [21]                     | ✓          |        |
| Goyal [38]                          | ✓          |        |
| Benkamoun et al. [23]               | ✓          |        |
| Hashemi-Petroodi et al. [25]        | ✓          | ✓      |
Machine Health Digital Twin. The system studied is a manufacturing system composed of three stations. Station 1, is a machine dedicated to the manufacturing of a single type of product which is a pen. Station 2, Control, is used to control the quality of all products. Station 3, the rectification is dedicated to the repair of defective parts received as a result of the control stage. The machine produces at a rate \( i \) which depends on the stock level. Each product leaves the machine and enters the control station for a time \( T_{\text{contr}} \). After the control, the pens which pass control will go directly into the stock while the defective ones will be reworked at the correction station during a time \( T_{\text{cor}} \) before going into the stock. The final stock is composed of two flows: flow 1 of those which passed control and flow 2 of reworked parts. The idea of using the digital twins for a simulation is to allow the connection of real data when reconfiguring our system. The simulation in this case allows the decision making to implement a reconfiguration through the triggers. The design of RMS implemented is composed of the three types of reconfiguration (physical, logical and human) (see Fig. 1).

In the literature, we note the lack of work dealing with the human aspect in the reconfiguration of the manufacturing system. Given the complexity of dealing with the human aspect in its entirety, we will limit ourselves in this article to the skills of the operators to perform an operation. Human reconfiguration involves human resources (operators, administrators, controllers) and operator training. Many works in the literature consider that their reconfigurable manufacturing system can be implemented at a high level of automation, which does not necessarily require human resources. We consider that this reasoning has limitations, because even if the manufacturing system is at a high level of automation, operators are still needed to supervise the manufacturing cell and maintain the equipment. We start with a proposal of the generic models proposed in SysML which will be transformed into Python programming language using the Visual Paradigm for UML software. The objective is to offer a quick solution to the new configuration, providing compatible sequences of operation outputs. Subsequently, a simulation by the digital twin. We applied these developments to an assembly process system. This model can also be deployed on other assembly systems that regularly need to be reconfigured quickly and effectively.

### 3.1 Structure

The structure defines all the resources, capabilities and skills, the products and the means of communication between these elements. The structure is a triplet:

\[ S : \{ Sp, Sl, Sh \} \]  

\( Sp \) denotes the physical structure, \( Sl \) represents the logical structure and \( Sh \) represents the human structure. \( Sp \) is the physical structure, described by the triplet:

\[ Sp : \{ R, \text{Capab}, \text{Conn} \} \]

where \( R \) represents all the resources of the structure (stationary resources, transport resources and maybe AGV mobile robots), \( \text{Capab} \) describes the capabilities of each resource and \( \text{Conn} \) represents the connection application such as:

\[ \text{Conn} : R_s \times R_s \times R_t \rightarrow \{0, 1\} \]

where \( R_s \) represents a stationary resource, \( R_t \) represents a transport resource and \( R_m \) represents a mobile resource. Each connection links two stationary resources through a transport resource or a mobile resource that performs the transfer.

\( Sl \) is the logical structure represented by the quintuplet:

\[ Sl : \{ F, G, \text{Prec}, \text{Af fec} \} \]

where \( F \) is the set of functions (\( F_{\text{tr}} \): work functions, \( F_{\text{ts}} \): transport functions and \( F_{\text{st}} \): storage functions), \( G \) is the set of logical ranges (sequences of functions) and \( \text{Prec} \) is the set of
types of products. The Prec application defines the priority relation between the functions within a logical range:

\[ Afec : G \times Pr \rightarrow \{0, 1\} \]  

(5)

Sh is the human structure represented by:

\[ Sh : \{R, Comp, Ref\} \]  

(6)

where R is the set of mobile resources (human and operational), Comp is the set of necessary skills and Reaf is the reallocation of work tasks. The Reaf application allows you to assign one or more tasks to a mobile resource according to its competence.

\[ Afec : Rm \times Comp \rightarrow \{0, 1\} \]  

(7)

Workstations are characterized by resources and are linked to specific tasks (operations) and to a location in the factory (Cartesian coordinates). Resources can be operators, tools, robots or machines, which are legacies of the “Resource” class. This figure represents the S structure from a particular point of view, called a meta-model, which illustrates the modular components to build and the relationships which ensure the flow of information between these components. The “Structure” block represents the structure of the system has three relationships, with the physical structure, the human structure and as well as with the logical structure (see Fig. 2). The physical structure is made up of resources and connections. Each resource has capabilities and skills; three types of resources are considered: stationary resources (workstations, first aid stations and buffers), transport resources (conveyors, robots and loader / unloader) and mobile resources (AGV if necessary and human).

With regard to workstations, the “Ports” block defines the characteristic locations for transfers. The connections are represented by the “Connections” block, they connect the workstation ports by means of a conveyor or a robot. At the level of the logical structure, three types of functions

Fig. 2 Meta-model of the structure
are defined: work functions which intervene in the production of goods also taking into account the control-inspection functions, transport functions which are associated with the connections and storage functions which connect the loader/unloader to buffers. The “Products” block represents the types of products described by the “Range” logical ranges which represent the sequences of functions. The “Priority” block defines the precedence relation between the functions within a logical range. The “Assignment” block associates one or more logical ranges with all types of products.

The human structure is made up of mobile resources. Each resource (mobile robots (AGV if necessary) and human) has capabilities and skills. It also relates and to the assignment of operators or robots to different workstations. This assignment of operations to operators is carried out in relation to a skill scale. When an operator does not have a skill required to perform an operation, he will be trained on this skill through operator training.

### 3.2 Configuration

A configuration is a state of the system that responds to a particular context. To define the system configuration, we must define a set of system parameters that determine this configuration. Changing a parameter implies changing the system configuration. The number of machines, the number of assembly lines, the number of loading stations, the number of AGVs in the workshop, the number of operators, the positioning of these objects in the workshop, AGVs fleet management rules, etc. are some examples of configuration parameters. The configuration of a reconfigurable system represents the part of the system that evolves according to the hazards, changes in the environment or modifications of the objectives set for the system. Based on the two definitions, we can define a system configuration which is a structure broken down according to the logical axis (takes up the functions used by instantiating them), physical (describes the different transfers used as well as the resources used) and human (reassignment of tasks) (See Fig. 3).

\[
C : \{ Cp, Cl, Ch \} \tag{8}
\]

where \(Cp\) is the physical configuration, \(Cl\) the logical configuration and \(Ch\) the human configuration.

\(Cp\) defines the physical configuration, described by the pair:

\[
Cp : \{ R_{util}, CapabAssoc \} \tag{9}
\]

where \(R_{util}\) represents the set of resources used in this configuration, this set is included in the global set of \(R\) resources. In addition, \(CapabAssoc\) defines the capabilities associated with each resource and thus, for each resource, some modules (tools and / or devices) may be used. In addition, the \(RessUtil\) application allows to declare what resources are used among those of the structure in this configuration.

\[
RessUtil : R_{util} \times R \longrightarrow \{ 0, 1 \} \tag{10}
\]

Therefore, the physical configuration is a main indicator for evaluating this configuration at the cost level. On the other hand, the logical configuration represents the set of control programs corresponding to the products, the logical ranges as well as the configurations:

\[
C : \{ prog \} \tag{11}
\]

The implant application allows you to implement a control program on each resource used in the current configuration:

\[
Implant : Prog \times R_{util} \longrightarrow \{ 0, 1 \} \tag{12}
\]

where \(Rm\) represents the reallocation of mobile resources used in this configuration. At the level of each resource, the \(CompAssoc\) application allows you to specify the skills associated with this configuration

\[
CompAssoc : Comp_assoc \times Comp \longrightarrow \{ 0, 1 \} \tag{13}
\]

The configuration block represents a possible configuration of the system and has three relationships with the physical configuration, the logical configuration and the human configuration (Fig. 3). The physical configuration block is made up of resources and connections. Each resource has capabilities; three types of resources are considered: stationary resources (workstations, first aid stations and buffers), transport resources (conveyors, robots and loader / unloader) and AGV mobile robots. The logical configuration block represents all the control programs corresponding to the products, the logical ranges and the configurations. The human configuration block involves the reallocation of human resources (administrators, operators and controllers) or the reassignment of work tasks. We also have operator training. To reconfigure a work task, we must take into account of the operator’s skills. Indeed, the adhesion of human capital through the mobilization of its skills constitutes an effective lever to achieve the objectives and improve the performance of the company. Moreover, better identification of skills and a distinguished presentation of preferences are two conditions for a more precise modeling of constraints taking these resources into account in their workplace. A variety of significant works have focused mainly on human resource allocation issues with skills taken into account. Some consider the difference between operators as a factor having a direct impact on the performance of the reconfiguration. Our system is made up
of human present and permanently available resources. Each of these resources is characterized by a skill profile. Their speed of processing does not only depend on the task. Each resource has a qualification level for each of the skills required by the tasks. Operators will more or less quickly process a task. Our objective is to link the notion of skills needed to the assignment of tasks given in order to assess the impact on some of the decisions to choose the reconfiguration. We distinguish the concept of skills as being a knowledge and the actor’s profile which provides information on all the skills acquired by an actor. Bruccoleri et al. [15] identify several skills required to perform operations in a manufacturing system. The skills considered are: operation and control, loading and monitoring, adjustment, maintenance, assembly and overhaul of machines, programming of machines, which can be skills of local actors. In addition to these skills, we suggest taking into account team management and site management skills.

3.3 Operation

Operations occupy a central role in models of reconfigurable production systems. Using the definition given in [17], “An operation is a function performed on a product by a resource taking into account its spatial situation within the system”. It is therefore the operations which are at the center of the breakdown of the system and which link the physical part describing the resources to the logical part defining the functions. The link between structure and configuration is also made through operations defined in the structure by identifying needs and constraints selected in the configuration. The operations then occupy a central role in the model; since they associate the functions with the resources, they link the architecture with the configurations and the physical part with the logical part. We distinguish between two types of operations which are local and collaborative. In collaborative operations, we have the implementation, machining and assignment operations. Local operations are storage and

Fig. 3 Meta-model of the configuration
transport operations (see Fig. 4). The transfer type operation implements a change in the physical location of the product. It is executed by elements (loading/unloading robot, part of conveyor) of the transport system. We emphasize that a conveyor, which offers the possibility of connecting several places, performs several transfer operations. The other operations are of the stationary type. Their characteristic is a unique place of achievement. The machining type operation implements the transformation of a part (turning, milling, etc.). The output part corresponds to the transformed input part. There is conservation of the flow. The definition of a machining operation is based on the machining location and the function of a processing resource (lathe, machining center, etc.).

The storage type breaks down into active storage and passive storage. The passive storage type operation involves immobilizing a part in a physical location. It is defined from a physical location that can receive one or more products that do not undergo any transformation. The active storage type operation is similar to the passive storage type operation, except that an order is required to perform the operation. This type of operation can be carried out by a stop in the extended position, on a conveyor. In addition, the operation sequences can be represented by an operation sequences block. Thus, each sequence of operations is associated with the logical range of a product. A sequence of operations is meant to achieve of operations to achieve the logical range of a product. Consequently, operations represent another main indicator for evaluating this configuration in terms of operating time. At the workshop level, we distinguish six types of operations: main operations, transport operations, storage operations, activation operations, assignment operations and implementation operations. The machining operations are defined by the Usinage operations block; this is an example of work associated with machines. Each machine must perform at least one main operation and each function is implemented by an operation. For example: Op1 (M1, F_tr_1). The following application describes the operations implementing the work functions on the associated workstations.

![Meta-model of the operations](image-url)
The transport operations are represented in the Transport operations block, each transport operation being linked to a transfer (connection) and to a corresponding transport function. The second application defines the operations associating the transport functions with the different connections:

\[ \text{Op}_{\text{transport}} : Op \times F_{ts} \times conn \rightarrow \{0, 1\} \]  

The storage operations store the products in buffer memories IN and OUT; they are described in the Storage operations block. \( \text{St0(Pr0, IN)} \) is used to store the \( \text{Pr0} \) raw product in the buffer IN and \( \text{Stj (Prj, OUT)} \) allows to store the final product (finalized on one of the workstations of m phase) in the buffer OUT. He defined an application that describes these Operations:

\[ \text{Op}_{\text{stockage}} : Op \times F_{st} \times \text{Tampons} \rightarrow \{0, 1\} \]  

Assignment operations allow to activate the resources used in a configuration. This part of the resource will then be eligible to use:

\[ \text{Op}_{\text{affectation}} : Op \times R_{util} \rightarrow \{0, 1\} \]  

The implementation operations allow the implementation of control programs on each resource used in this configuration. For example, in a process plan, he activated the required operations on a machine while deactivating the other operations that this machine is capable of performing:

\[ \text{Op}_{\text{implantation}} : Op \times \text{Prog} \times R_{util} \rightarrow \{0, 1\} \]  

### 3.4 Simulation RMS-DT

The emergence of the digital twin enables real-time interaction and integration between a physical system and an information system. A digital twin acts as a mirror of a real-world object, providing a means to simulate, predict and optimize physical manufacturing systems and processes. Digital twins can consist of physical models in virtual space, which can simulate the behaviors of their physical processes and provide real-time feedback. The characteristics of a digital twin are:

- Virtual models are faithful replicas of physical entities, which reproduce physical geometries, properties, behaviors and rules.
- Services (simulation, verification, monitoring, optimization and diagnosis)
- Data
- Connections

In this section, an approach to modeling digital twins with MATLAB and Simulink is presented. Before that, the graphical interface (man–machine) is presented. The man–machine interface is used to ensure the best possible interaction between the physical and virtual parts of the digital twin. After presenting the diagrams of the meta-model, we will automate them to have a man–machine interface for reconfiguration. The goal of this work is the accessibility and the automation of the reconfiguration. Here are the steps to set up the reconfiguration interface:

- Write the various blocks of the diagrams in object programming form. When object programming is used, the blocks become separate classes containing attributes. Our goal was to present the diagrams in code form and for this we need a software with reverse code. We chose the Visual Paradigm software for UML.
- Code generation with Visual Paradigm. In order to better manipulate the classes, it is necessary to use the same logic with the primary and foreign keys in the database, this allows to link the classes between them.
- Now that the classes are modeled, we set up an interface. The interest of this interface is to make the reconfiguration accessible without prior training.

The interface will be in the form of a window. Through it, a series of questions can be answered that will allow the reconfiguration to be triggered and the necessary reconfiguration to be implemented. This allowed us to automate our reconfiguration (Fig. 5).

In our work, we model the system as signals flowing through different blocks (Fig. 6). Here the signals represent the key characteristics of the modeled manufacturing system. These signals, through blocks allow the calculation of the outputs, the system states and the integration of its dynamics. Our system is composed of four blocks, the machine block emits three signals. The first one indicates the state of the machine. There are three possible states. The first is running, (when the machine is working properly). The second is stoppage of the machine; either for preventive maintenance, or for reconfiguration, because of the introduction of a new product. The third is failure that triggers a reconfiguration action or corrective maintenance.
of the machine. The second signal gives the actual age running time of the machine and the third signal indicates the number of products left before preventive maintenance. The signal rate feeds the machine block, which allows the block to calculate the age of the machine through usage. The buffer block has two streams, the input rate and output rate signals.

There are also relays that allow the block broadcasting to other blocks to be detected. The control block sends signals of production rate and age of the machine and also the control. It broadcasts two signals, one with approved parts and the other with rejected parts. The correction block uses the signal from the rejected parts, simulates the rework and then sends with the rectified parts. The signal of the rectified parts and the good parts feeds the buffer block. This simulation allowed accurate results to be obtained with respect to the event triggering reconfiguration giving a faster execution time, allowing a reconfiguration to be performed as fast as possible within a given time frame. Data acquisition is a crucial part of implementing a digital twin of manufacturing systems. Equivalently, the digital twin is a physical entity that communicates with a “virtual” or “cyber” model, which has data processing modules. These digital twins connect to cloud services, use a shared knowledge base or library and can potentially communicate and collaborate with others. After data acquisition, a concept for data storage, including interfaces, is needed. The goal is to provide a solution for data storage, building on existing cloud solutions.

The digital twin exists in two forms: the static digital twin, which allows validation of different scenarios of a process before its physical implementation, and the dynamic digital twin, which allows supervision of the manufacturing in real time, on the basis of machine information according to well-defined problems. In our case, it is a question of developing an approach to deployment of digital twins in real time. The power of real-time digital twins lies in their ability to make it possible to analyze and respond to thousands of data sources in real time (Fig. 7). We apply the idea of a classical real-time analytics pipeline to our system. A classical pipeline combines the IoT from all data sources into a single stream that is queried by the user’s real-time analysis application. This code often takes the form of a set of SQL queries (extended with temporal windowing semantics) executed in real time to select events of interest from the stream. The results of these queries are then passed to a data lake for off line analysis using tools such as spark. Query results can also be passed to cloud-based server-less functions to trigger alerts or other actions in conjunction with database access such as Mysql or mongodb. These techniques are very effective in analyzing the IoT as a whole to identify unusual situations that may require action. One of the main limitations of this approach is that it is difficult to track and analyze the behavior of each data source (IoT) separately, especially when there are thousands or more of them. It is simply not practical to create a single query tailored to each data source. However, real-time digital twins easily put these capabilities at your fingertips. Finally, dynamic digital twins facilitate real-time aggregate analyses of state data across all instances to spot emerging patterns and trends. Instead of waiting for the data lake to provide information, real-time global analytics of the digital twins can immediately bring interesting patterns to the surface, maximizing situational awareness and helping to create response strategies.

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![Fig. 5 Graphic interface of the reconfiguration](image)

![Fig. 6 Representation of our system by block](image)
4 Case study

In order to show the interest of the approaches proposed in this thesis and also to immerse the theoretical developments in a real context, we have chosen the case study which concerns the assembly of pens. Indeed, this one regularly presents reconfiguration needs in a fast and efficient way. First, we present the company DEKENZ in which the work has been applied. Then, we introduce the manufacturing process and the system modeling. The DEKENZ company is a semi real/semi fictitious company created in 1998 around the flexible production line of the IUT of Montreuil. DEKENZ’s activity is based on the design, manufacture and marketing of mid-range pens. It has a major particularity that makes it special. In fact, every year a new team takes over and takes responsibility for the DEKENZ company. The manufacturing system consists of two workshops (Fig. 8):
(i) The manufacturing workshop which includes:
- Machining machines (milling machines C3000 and C4000 and lathe G2009)
- A storage magazine for MP and PF
- An injection molding machine

(ii) The assembly and finishing workshop comprising
- Tribofinishing
- The engraver

The product is composed of two components, the pen body and the tip. On the pen body it is necessary to have the customer branding. Obviously, each customer requires a unique branding, differentiating the productions of what is essentially the same pen model. This creates a differentiation for customization. For pens of the same model, the main body is exactly the same, except for the brand. The process can be summarized in the Fig. 9 below:

This company manufactures personalized pens with the following composition:
- Body: metal for Pr1 and plastic for Pr2
- Head: metal for Pr1 and plastic for Pr2
- Ink chamber
- Spring
- Silicone holder (for Pr2)
- Staple for the product Pr1
- Knob: metal for Pr1 and plastic for Pr2

The products manufactured by the company are:
- Normal pens for the other age categories: A Pr1 Product Family
- Pens for children: a family of Product B: Pr 2 (clip and pusher)

Each product is manufactured in 2200 s and it takes 800 s to have a personalized product. The Pr1 product follows a specific manufacturing process. Raw materials in the form of aluminum bars are loaded by operator OP1 to be cut into strips. Then they go through two types of machining: the first is turning and the second is milling to obtain the body, head, clip and pusher. Then the clip will be engraved. All these components pass through the control station to check their measurements, then through the tribofinishing and on to the assembly where the operator adds the ink chamber and the spring. Finally, a finished product is obtained which undergoes final inspection and will be stored. The Pr2 product follows a well-defined manufacturing process. The raw materials, which are polystyrene and silicone, are injected separately into the injection molding machine to form the polystyrene body, head and pusher and the silicone support. These components will be controlled and then assembled by adding the spring and ink chamber to obtain the Pr2 finished product which will be controlled and stored. The modeling of the general manufacturing process is given in the Fig. 10 below.

Detailed manufacturing process of the fountain pen: First of all, the raw materials (PM) coming from the magazine M

Fig. 9 Detailed manufacturing process of the pen
(brass for the cap, body and clip) go through the pre-machining operations U1 (cutting, filing) and then to the machining stations either to milling directly F for the clip or to turning only T for the body, the nose (feather block trim) and the end caps or to turning and then milling for the cap. After machining, the clip has two possible paths either to engraving G and then to post-machining operations U2 or to the magazine for subcontracting ST (gilding, silvering and anodizing). For the other components, they go to the U2 post-machining operations, which are inspection and tribofication, and then to subcontracting through the magazine. For the clip, the process begins with the reception of the raw material (polyethylene) that will be injected in the Pclip injection molding machine and then undergoes the post-machining operations U2 to be transferred to the subcontracting ST through the M warehouse. All the components of the pen are manufactured, so they are ready for assembly, which is carried out in two stages, the first is the partial assembly A1 of the cap and body components and the second is the final assembly A2 of the pen, adding the clip and the cartridge to the cap and body, so a finished product is obtained which will go through the final inspection and then be packed, stored and finally distributed.

**Inputs**

The stationary resources are:

- M1: workstation that performs the operations before machining (cutting, filing)
- M2: Milling machines (C3000 and C4000)
- M3: CN lathe (G2009)
- M4: Engraving machine
- M5: Workstation that performs the control of measurements
- M6: Tribofinishing
- M7: workstation that performs subcontracting operations
- M8: Workstation that performs assembly 1
- M9: Workstation that performs assembly 2
- M10: Injection molding machine
- IN
- OUT

The human structure is composed of mobile resources and transfer resources.

**Transfer resources:**

- Conveyor
- Operators: H1, H2, H3, H4, H5, H6, H7, H8, H9, H10.

Assignment of operators to workstations according to tasks (Main operations). In order to better make the assignment of the operators, we identify their competence and for that each operator is noted with a weighting in order to be able to differentiate and to know which one will be the most brought to carry out a task (principal operation) rather than another. We use an algorithm to make the assignment of the tasks (Tables 2, 3, 4, 5, 6, 7, and 8).

**Outputs**

With MATLAB, we can define a model using data from production resources. We will also use Simulink to create a physics-based model using the multi-domain modeling tools. The data-driven and physics-based models can be fitted with equipment data to act as a digital twin. We will use these digital twins for prediction, anomaly detection and hypothesis simulation. Data-driven methods available in MATLAB include workstations and system identification. Datasets are typically used to perform training or model extraction. A separate validation dataset is also used to qualify or test models. Simulink allows the study of linear and nonlinear systems modeled as continuous, discrete

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**Table 2** Assignment of operators to workstations according to tasks (main operations)

| Operator/Op | Op1 | Op2 | Op3 | Op4 | Op5 | Op6 | Op7 |
|-------------|-----|-----|-----|-----|-----|-----|-----|
| H1          | 6   | 5   | 6   | 6   | 8   | 2   | 4   |
| H2          | 3   | 8   | 7   | 8   | 4   | 5   | 4   |
| H3          | 1   | 3   | 6   | 2   | 8   | 9   | 5   |
| H4          | 2   | 3   | 5   | 9   | 4   | 9   | 9   |
| H5          | 4   | 1   | 6   | 7   | 5   | 6   | 9   |
or hybrid. The system can be single-cycle (single rate) or multi-cycle. Simulink is also an add-on program to MATLAB for the simulation of dynamic systems. Controlling and modeling systems become easier; transfer functions are written as blocks and connections are made by oriented arcs. Different types of signals can be generated and visualized using virtual instruments. A model built using an assembly of elementary blocks can be encapsulated. It can then be added to the library available in Simulink. For each simulation of a system, Simulink creates a function file S. Simulink has two important tools (libraries):

(i) SimEvents: simulates discrete event systems (DES). It is fully integrated with Simulink. We have an efficient coexistence of event-driven components in complex hybrid systems.

(ii) Stateflow: model and simulate combinatorial and sequential decision logic based on state machines and flowcharts. It is fully integrated with Simulink.

With these features, MATLAB/Simulink is a platform that offers a multi-paradigm tool for modeling complex systems. The system studied is a manufacturing system composed of three stations, as shown in the figure. Station 1, is a machine dedicated to the manufacturing of a single type of product which is the pen. Station 2, Control, is used to control the quality of all products. Station 3, grinding, is dedicated to the repair of defective parts through inspection. The machine produces at a rate i and is dependent on the stock level. Each product leaves the machine and enters the inspection station for a time (Tcontr). After the control, the good product goes directly into the stock and the defective ones are reworked by the correction station for a time (Tcor) before going into the stock. The final stock is composed of two flows: flow 1 of good parts and flow 2 of reworked parts. The idea of using the digital twins through a MATLAB/Simulink simulation is to allow connection to the real data when reconfiguring our system. The simulation in this case allows the decision making to implement a reconfiguration through the triggers.

For a product, we can choose a corresponding logical range and with several operations of the range which can be carried out on the same workstation. We choose the set of resources capable of performing all the functions of this range, namely the resources used: this represents the first part of the physical configuration. Thereafter, we define the connections (the scheduling of the stations) and the assembly operations (main operations, transport, storage, assignment, activation) (Fig. 11).

To achieve the finished product, several manufacturing, finishing and assembly operations are carried out. We define the main operations. For example, Op1 (M1, F_tr1, H1) is a machining operation and Op4 (M3, F_tr3, H2) is an engraving operation which is carried out by removing materials. The engraving allows you to personalize the pen. The injection molding machine makes it possible to manufacture the clip which ensures that the cap is properly closed. Tribofinition is a technique for polishing rough elements. The control operation covers the sides specified by the design office. The assembly is an operation making it possible to produce the pen by assembling the various semi-finished products. We define the other operation sequences, such as Op_st_in, Op_ts1 ... Op_ts4 and Op_st_out. Suppose, for example, that a failure suddenly occurs on the M4 machine, the habit is to stop the line to be repaired and then continue with the production plan. On the contrary, the generic model of SPR proposed in this article allows to reconfigure this line quickly and efficiently by modifying the resources, the associated capacities, the skills through the training of the workers to make them work on another workstation and the programs currently used for each component of the new structure. As a result, we are reallocating new operations to new resources. Compared to the distribution of operations, the H4 worker no longer has a task to perform, so he can be trained to be assigned to another position. Thus, the reconfiguration function reduces time with all the positive consequences in terms of logistics. Consequently, the use of an RMS-DT will help improve the quality of service and will offer several advantages. Compared to the distribution of operations, the H4 worker no longer has a task to perform, so he can be trained

| Parameters | Designation |
|------------|-------------|
| F_tr8      | F_tr9      |
| F_tr10     | F_tr11     |
| F_tr12     | F_tr13     |
| F_tr14     | F_tr15     |

Table 3 The work functions as follows

Table 4 Logic ranges

| Parameters | Designation |
|------------|-------------|
| G1         | F_tr1, F_tr2, F_tr3, F_tr4, F_tr5, F_tr6, F_tr13, F_tr14, F_tr15 |
| G2         | F_tr9, F_tr7 |
| G3         | F_tr10, F_tr8 |
| G4         | F_tr11, F_tr7 |
| G5         | F_tr12, F_tr7 |

Table 5 Storage functions

| Parameters | Designation |
|------------|-------------|
| F_st_in    | Zone tampon IN |
| F_st_out   | Zone tampon OUT |
to be assigned to another position. Thus, the reconfiguration function reduces time with all the positive consequences in terms of logistics. Consequently, the use of an RMS-DT will help improve the quality of service and will offer several advantages (Fig. 12).

5 Managerial implications

In order to ensure that the design and simulation model was not limited to the design of the manufacturing lines in the subject company, the content of the design model was exclusively based on theory. The concept of the simulation model, however, was based on both design model theory and ease of use in the industry and feedback from the subject company through the focus group. By including the industry perspective on the use of the digital twin design model, it was ensured that this model unlike other previously developed design and simulation models for reconfigurability, is applicable in industry. The application of this proposed model would be to evaluate the ability of production lines to respond quickly to a disturbance. The ease of obtaining data to implement the digital twin deployment is a testament to the usability and feasibility of our approach. In this study, the digital twin design and simulation was designed to cover only the reconfigurability of manufacturing aspects, and thus the development of the design model for the system level was considered more appropriate. This is a great advantage over the work discussed in the state of the art. When implementing the model, special attention was paid to error prevention, as well as flexibility and efficiency of use. In addition, the COVID19 pandemic has caused unprecedented disruption to production operations, with new demands for healthcare products, extreme delivery requirements, production and distribution restrictions. More than ever, manufacturers are looking for machines that are both intelligent and reconfigurable to respond dynamically and quickly to demands of today and tomorrow, and throughout the life cycle of their products. In addition, customers are demanding faster delivery times. Due to capacity limitations, the company cannot meet the delivery requirements of all orders accepted after COVID19. The company may choose to increase its capacity by installing more machines and hiring more employees to be able to meet customer orders. To overcome the problems they face, companies have chosen to reorganize the manufacturing process rather than increase capacity. By following the steps of designing the reconfigurable manufacturing system with digital twin simulation, we were able to reorganize the manufacturing process in the case study and the model was successfully implemented. According to the suggested steps, the first thing to do is to identify the potential changes in the particular situation. With the description of the product and manufacturing process above, it is easy to quickly make changes in this context. It is these changes that make the products custom. We have run several scenarios from the human–machine interface to study the automatization of the proposed model. The use of the RMS-DT model in the industry as presented in the case study allowed the effect of actions needed to correct or improve performance on the virtual system to be simulated prior to their implementation on the physical system. This step is repeated until satisfactory performance is achieved. With this tool, managers can set performance targets in advance. Indeed, when defining the objectives, it is possible to simulate the operation of the system in order to verify the achievability of these objectives.

| Parameters  | Designation                        |
|-------------|------------------------------------|
| F_st_in     | the raw material is available on IN |
| F_st_out    | the finished product (the fountain pen) is stored on OUT |

| Parameters  | Designation                        |
|-------------|------------------------------------|
| Op1         | cut (operation before machining)   |
| Op2         | machining (fraisage)               |
| Op3         | machining (tournage)               |
| Op4         | engraving                          |
| Op5         | controle                           |
| Op6         | tribofinition                      |
| Op7         | gilding                            |
| Op8         | silvering                          |
| Op9         | black coloring                     |
| Op10        | night blue coloring                |
| Op11        | red coloring                       |
| Op12        | green coloration                   |
| Op13        | assemblage 1                       |
| Op14        | assemblage 2                       |
| Op15        | press                              |

| Parameters  | Designation                        |
|-------------|------------------------------------|
| F_ts1       | transfer from IN to M1             |
| F_ts2       | transfer from M1 to M2             |
| F_ts3       | transfer from M2 to M3             |
| F_ts4       | transfer from M3 to M4             |
| F_ts10      | transfer from IN to M10            |
| F_ts11      | transfer from M9 to OUT            |

| Parameters  | Designation                        |
|-------------|------------------------------------|
| F_tr1, M1   | cut (operation before machining)   |
| F_tr1, M2   | machining (fraisage)               |
| F_tr3, M3   | machining (tournage)               |
| F_tr4, M4   | engraving                          |
| F_tr5, M5   | controle                           |
| F_tr6, M6   | tribofinition                      |
| F_tr7, M7   | gilding                            |
| F_tr8, M7   | silvering                          |
| F_tr9, M7   | black coloring                     |
| F_tr10, M7  | night blue coloring                |
| F_tr11, M7  | red coloring                       |
| F_tr12, M7  | green coloration                   |
| F_tr13, M8  | assemblage 1                       |
| F_tr14, M9  | assemblage 2                       |
| F_tr15, M10 | press                              |
Fig. 11  Presentation of the initial configuration

Fig. 12  New configuration
6 Conclusion

With a sharp increase in the demands of healthcare products and the office caused by the COVI-19 crisis, reconfigurable manufacturing system has become increasingly important. This paper provides a comprehensive tool for RMS-DT design and simulation with intelligent sensing and simulation functions, which makes production more efficient and intelligent. Furthermore, the integration of artificial intelligence into the RMS-DT framework has improved the performance of digital twins by applying machine learning (ML) for prescriptive analysis in production, which has facilitated flexible decision making at the design stage. In the future, the idea is to study the RMS features by integrating them into this RMS-DT model. Therefore, in future research it will be necessary to determine the real production conditions and to take into account factors such as production cost and resilience, in order to obtain evaluation results that are still very close to reality. The ability to recover and succeed after a failure is defined as resilience [39]. A resilient production line is able to reconfigure its structure and resources to achieve the desired functions. Zhang and Lin [40] consider it crucial to be able to measure the success of a production line after a failure in order to provide managers with a broader understanding of the system, thereby improving the system’s ability to respond to market changes.

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Declarations

Ethics approval The authors declare compliance with ethical standards.

Consent to participate The authors consent to participate.

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