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A Systemic approach for Material Handling System Design

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***Abstract* –** Mastering internal logistics is a crucial issue for numerous companies due to their impact on production costs and production system performances. The design of such systems is very complex, especially with the introduction of industry 4.0 technologies that bring new interactions with various technologies. Many questions arise on how to propose an efficient Material Handling System in which several Material Handling Equipment interact with each other in the demanding environment of production systems (operators, ERP, manufacturing system, etc.). This context of Material Handling Systems design implies considering a systemic approach to address its completion, nevertheless, this has not been the observed trend in the existing literature. Many practices in Material Handling System design and management can be found which are diversified and without a consensus on how to efficiently design these systems. In this paper, we propose a Material Handling System (MHS) design approach following the principles of Systems Engineering defined by The International Council on Systems Engineering (INCOSE). It starts with the needs and requirements identification through Model-based Systems Engineering techniques. Then based on the gathered data, a set of potential solutions is made. A method is then defined to drive the performance evaluation of the alternatives through partially-generated simulation models. Finally, a multi-criteria decision approach is provided to embed a wider range of decision parameters in the final selection round for the most suitable solution. The purpose is here to imply heterogeneous criteria coming from operational or tactical constraints of the companies (ex: safety concerns, procurement policy, competency management …). This paper summarizes and illustrates the different methods and tools that can be used along the proposed workflow for the design of Material Handling Systems.

***Résumé* –** La maîtrise de la logistique interne est un enjeu crucial pour de nombreuses entreprises en raison de son impact sur les coûts de production et sur les performances du système de production. La conception des systèmes de logistique interne peut s’avérer complexes en raison des multiples interactions en jeux. La question est aussi renouvelée avec l'introduction des technologies de l'industrie 4.0. De nombreuses questions se posent sur la manière de proposer un système de manutention efficace dans lequel des équipements de technologies différentes interagissent entre eux et avec leur environnement (opérateurs, ERP, système de production, etc.). Dans cet article, nous constatons l'absence d'une approche globale pour aborder la conception des systèmes de logistique interne. La littérature présente de nombreuses pratiques de conception et de gestion des systèmes de manutention qui sont diversifiées mais sans consensus sur la façon de concevoir efficacement ces systèmes. Nous proposons de définir une approche s’appuyant sur les principes de l'Ingénierie Système (tels que définis par INCOSE). Nous proposons ainsi une approche systémique couvrant les phases importantes de la conception, en commençant par l'identification des besoins et des exigences en utilisant une approche structurée par les données récoltées. Vient ensuite la proposition d'alternatives de conception générées en exploitant les caractéristiques du besoin. Une méthode d’analyse de la performance est alors couplée pour analyser ces alternatives. L’approche propose également de conduire la sélection du système adéquat par l’utilisation d’une méthodologie d’analyse multicritères pour coupler les analyses quantitatives avec une évaluation plus qualitatives des priorités de l’entreprise en terme contraintes opérationnelles ou tactiques (choix de fournisseur, sécurité, intégration…). Ce travail résume et illustre les différentes méthodologies et outils qui peuvent être utilisés pour les différentes étapes de la conception du système de logistique interne définies dans cette approche.

***Mots clés* – Conception des systèmes de logistique interne, Ingénierie Système, Industrie 4.0.**

***Keywords* – Material Handling System Design, Systems Engineering, Industry 4.0.**

1 INTRODUCTION

Nowadays, industries are facing two main trends: mass production and mass customization which require a low response time and production cost (Avitabile, 2022). To meet these new requirements and trends, production processes have to be fed with the right amount of parts at the right time. Material Handling Systems (MHSs) contributes to such objectives (Avitabile, 2022). In the context of this paper, MHS is defined as a set of interacting Material Handling Equipment (MHE) that executes the storing, packaging, and moving of materials within the manufacturing system. The cost of Material Handling Operations (MHO) is far from being negligible, it ranges from 15% to 70% of the total manufacturing costs depending on the type of production (Hellmann et al., 2019). Moreover, the MHS plays a key role in the performance of the entire manufacturing system (Beamon, 1998; Esmaeilian et al., 2016; Soufi et al., 2023).

The design or modification of such systems is known to be very complex due to the various aspects that must be included during this process, e.g. MHO allocation, fleet size determination, or dispatching rules of MHEs creation. The MHS can be the cause of excessive spending and the deterioration of manufacturing performance if it is not well-designed (Bouh & Riopel, 2016). The complexity of the design process of MHS increased with the new challenges that were brought by Industry 4.0. It is, for instance, about finding the relevant level of automation to conduct the MHOs. The literature shows a lack of a systemic approach to conduct the design process of such systems. Various aspects of the design problem are addressed in the literature through different approaches, including (1) the **system's needs or requirements analysis** (Sendra et al., 2007; Starbek & Menart, 2000; Stephens, 2013), (2) **the MHS alternatives proposition** through the decision of the level of automation (Choe et al., 2015), (3) **the System's Performance Analysis** (Meng et al., 2013; Vieira et al., 2018), and (4) **the MHE Selection Problem** (Agarwal & Bharti, 2018; Gaur & Ronge, 2020; Hellmann et al., 2019; Kumar & Raj, 2016; Onut et al., 2009; Saputro et al., 2015).

In the literature, **the MHS Needs and requirements Analysis** is conducted through the Material Flow Analysis (MFA). MFA is defined as the assessment of flows and stocks of materials within a system defined in space and time (Stephens, M. P., & Meyers, 2013). MFA is addressed in various ways in terms of targeted data. For instance, in (Starbek & Menart, 2000) the authors focus on the analysis of the paths that are taken by different family parts. While in (Longo et al., 2005) additional aspects are included, such as the products' characteristics and dimensions. The existing MFA techniques mainly consist of manually executed and error-prone procedures such as building charts and diagrams. For example, From-To charts display the flow of material between the functional area of a plant (Stephens, 2013), Production sheets allow the collection of data relatively to each phase of the manufacturing process (Longo et al., 2005), and Flow charts allow the study of the material flow of each product family (Stephens, 2013).

The MHS alternatives definition consists in defining several scenarios where MHEs are selected and allocated to MHOs (such as transporting, storing, grabbing, picking, etc.). In the literature, the MHS alternatives definition is sometimes performed through the decision of the Level of Automation. It is defined as the allocation of physical and cognitive tasks between human and technology, described as a continuum ranging from totally manual to fully automatic (Frohm et al., 2008). These procedures rely on the use of the matrix of levels of automation and Square of Possible Improvements (Choe et al., 2015; Persson & Smedberg, 2019). The matrix of levels of automation describes the actions that could be carried in the different levels for both physical and cognitive tasks. The Square of Possible Improvements allows to identify potential level of automation of an MHO in terms of cognitive and physical automation. It is conducted based on the expert's knowledge and intuition. Such a procedure permits the proposition of MHS alternatives. E.g. if the Square of Possible Improvements of an MHO shows that the operation requires a higher cognitive level of automation, autonomous MHE can be proposed, such as Autonomous Intelligent Vehicles (AIVs). However, the application of such procedures can be difficult, time-consuming, and does not ensure the obtention of the best MHS alternative. Especially in the case of a large-sized plant, where several constraints and aspects (e.g. production rate, handling units' characteristics, physical constraints, the interaction between MHE, etc.) have to be considered. Furthermore, papers addressing the evaluation of MHS alternatives (Agarwal & Bharti, 2018; Onut et al., 2009; Saputro & Rouyendegh Babek Erdebilli, 2016) show that MHS alternatives are in most cases intuitively listed, restrainedly, and hardly justified. The MHS alternatives definition problem can be seen as a two-dimensional problem, the first one concerns the definition of the possible MHEs for the MHOs. The second one concerns the allocation of MHEs to MHOs including the fleet sizing problem. In the literature, the decision of MHE quantity (fleet sizing) is commonly addressed. Many approaches can be applied, for instance, authors use analytical approaches (such as queuing theory) to decide the number of homogenous MHEs (Chang et al., 2014; Raman et al., 2009). Other authors rely on simulation-based approaches (Mestiri & Fottner, 2022). In (Mestiri & Fottner, 2022), the authors highlight the complexity of dimensioning heterogeneous transport systems analytically due to their high complexity.

The System's Performance Analysis is needed to evaluate the system with indicators such as: on time deliveries, number of material shortages or product waiting time, etc. Such indicators are hard to predict without an approach considering the dynamic behavior of the MHS. Simulation-based approaches are popular for such analysis. However, the development of simulation models for MHS can be a tedious activity. For instance, it might be time-consuming (especially for modeling Large Scale Systems), difficult to build (some skills and knowledge are required to use simulation software), and hard to validate (Hao & Shen, 2008; Lee et al., 2018; Meng et al., 2013).

The MHE Selection Problem consists in selecting the right equipment amongst several MHE alternatives for a given MHO. This problem is addressed through three main approaches: Artificial intelligence, optimization, and Multiple Criteria Decision Making (MCDM). According to (Saputro et al., 2015), the MHE Selection Problem is mainly addressed using MCDM approaches. Although the MHE selection problem is commonly discussed in the literature, some limitations can be identified regarding how it is addressed. To name a few: a lack of justification for the choice of the MHE alternatives list, a lack of consideration of the interaction of MHEs with their environment, and a lack of justification of the criteria selected to be involved in the decision. The MHE operates in an environment with constant interaction and data exchange (E.g. with the operators, other MHEs, or the manufacturing systems). Thus, it is more convenient to address this problem from a systematic point of view. The selection problem should consider scenarios where different kinds of MHEs are allocated to MHOs and their impact on the whole manufacturing system.

The literature shows that the current practices for MHS design are scattered and devoted to separated sub-problems. Many practices are document-based and no global view of the MHS design problem is proposed. But regarding the complexity of the problem, it is relevant to adopt a more structured Systems Engineering approach and namely to deploy processes based on models and data (e.g. Model-based (MBSE) Data-driven Systems Engineering (DDSE)). The basis of DDSE is to organize the design activities around a common database available concurrently to all engineers and decision-makers of the project (Lindblad et al., 2018). Based on this database, a set of related system models can be developed through MBSE. The INCOSE highlights the importance of using MBSE throughout the different steps of the design; Needs and requirements identification, solutions/alternatives definition, performance analysis, selection and validation, and finally, the deployment of the solution. The combination of DDSE and MBSE practices, should, on one hand, insure consistency and ease the reuse of data throughout the MHS design project (Lindblad et al., 2018). On the other hand, it enhances the ability to capture, analyse, share, and manage information (Forsberg, K., & Krueger, 2011).

In this paper, an approach is proposed combining DDSE and MBSE for MHS design adopting a systemic view. It starts with the definition of a Reference Data Model (RDM) for the realization of the MHS needs and requirements analysis (1). The RDM aims to generalize the concepts brought through the needs analysis and to support the description of future MHSs. On one hand, it gives the ability to adopt a data-driven analysis that can generate different charts and diagrams to analyze the MHS while guaranteeing the reduction of development time, cost, and errors by ensuring data integrity. On the other hand, the RDM is used to develop a centralized database for the MHS design projects. Afterward, the proposal of MHS alternatives (2) is performed with a Constraint Satisfaction Problem (CSP) approach. MHS alternatives definition is a crucial step for the Material Handling System design. It allows the generation of many Material Handling Equipment combination possibilities where each equipment is allocated to one or several MHOs. Once the MHS alternatives are defined, an evaluation and a selection are required to choose the most adapted alternative for a given case (3). It is proposed to use a Multi-actors/Multi-criteria Decision-Making process with a list of 61 criteria organized into 11 groups (e.g. ergonomics, environmental, economics, human factor, etc.). Then, the selection process is supported by an evaluation of MHS performances (4) conducted through Discrete Event Simulation (DES). To support this evaluation, a generic, extensible, and scalable data-driven approach for MHS simulation model creation is developed. This approach helps to provide engineers with a formalized model where data retrieved from MHS needs and requirements analysis are transformed into Discrete Event Simulation (DES) models. The process allows the evaluation of the performance of MHS alternatives in a shorter time. The combination of the results of the last two steps (MCDM and performance evaluation) gives the decision-makers enough evidence to take the appropriate design and reconfiguration decisions.

The remaining of this paper is organized as follows: the next section describes our approach proposal for the MHS design through its four main phases. Afterward, the modularity of the approach is discussed to stress that the approach components can also be suitable for another kind of MHS design processes. Conclusions and perspectives are given in the last sections.

2 MATERIAL HANDLING SYSTEM DESIGN APPROACH

The purpose of this paper is to introduce an MHS design process addressing the complexity of the design problem with a structuration inspired by Systems Engineering approaches and supported by a toolkit. The process is based on a generic data structure that encompasses different MHS concepts addressed in the literature. The generic data structure helps to construct a centralized database for the MHS design projects. The database has an intermediary role between the different MHS design stages; It receives data from all of the interdependent MHS design steps, then, data are exported to define design alternatives, simulation models, analytical graphics, and charts. Figure 1 presents an overview of the proposed approach which is composed of four main steps (MHS needs and requirements identification, MHS alternatives definition, MHS performance analysis, and MHS alternatives selection). Each step is described through two boxes (plain and dotted). The plain box describes the theoretical development that led to the proposal of the approach. Then, the dotted box provides a view of how the approach can be used with the illustration of the developed toolkit supporting its implementation. The whole approach supports decision-makers throughout the process while ensuring data integrity (through data centralization) and reducing development costs and time (through the automatic generation of models). A description of each design step is presented in the sub-sections below;

2.1 *Material Handling System needs and requirements identification*

To address the design of any complex system, it is important to start with the identification of the system's needs. As cited in the previous section, the literature shows that MHS needs identification is performed in very dissimilar ways and most of the time with a restrained set of data. It is mainly done through error-prone and time-consuming manual procedures. These limits enhance the need of defining an RDM to express and organize the various relevant data expected for the MHS needs identification. To obtain a consistent RDM, 197 parameters were identified from industrial practical knowledge (Soufi et al., 2023) and articles discussing the system's needs analysis and MHS issues in general. Then, a classification of the terms that referred to the same concept was made with a selection of the most appropriate parameters to represent each concept. Through this process, redundancies were removed and only 57 relevant parameters were retained. As a result, a generic and extensible data structure is proposed and detailed in (Soufi et al., 2022). It regroups different parameters that allow a precise description of the MHS and an effective needs identification. The structure is composed of three main data categories; product (see Figure 2a), manufacturing system (see Figure 2b), and MHS (see Figure 2c). During the design process, the product data is to be first retrieved. It expresses the characteristics of the products, product families, and handling units. Afterward, Manufacturing system data focuses on the description of the production cells, machines, and queues. Finally, the MHS data describes two main aspects: the layout of the shop-floor and a classification of the MHS elements in terms of executed MHOs and used technologies.

In the toolkit supporting the process (see the top left square in Figure 1.) the structure of the RDM is used to develop a database using a database management software (Workbench MYSQL). The database allows inserting the required data for the realization of the MHS needs and requirements identification. Afterward, the data is exploited (see the top left square of Figure 1.) to generate simultaneously different MFA charts and diagrams such as from/to charts, flows charts, and 2d maps that help clarify the material flows. The data retrieved in this step are stored in the central database of the project and are important inputs for alternative generation and simulation model creation. The RDM and database are generic to permit their use in various industrial contexts. They are also extensible to provide a connection to the following step of the design approach (ex: for MHS alternatives description). The centralized data is available to generate models helping to reduce the cost, time, effort, and errors for the whole design project.

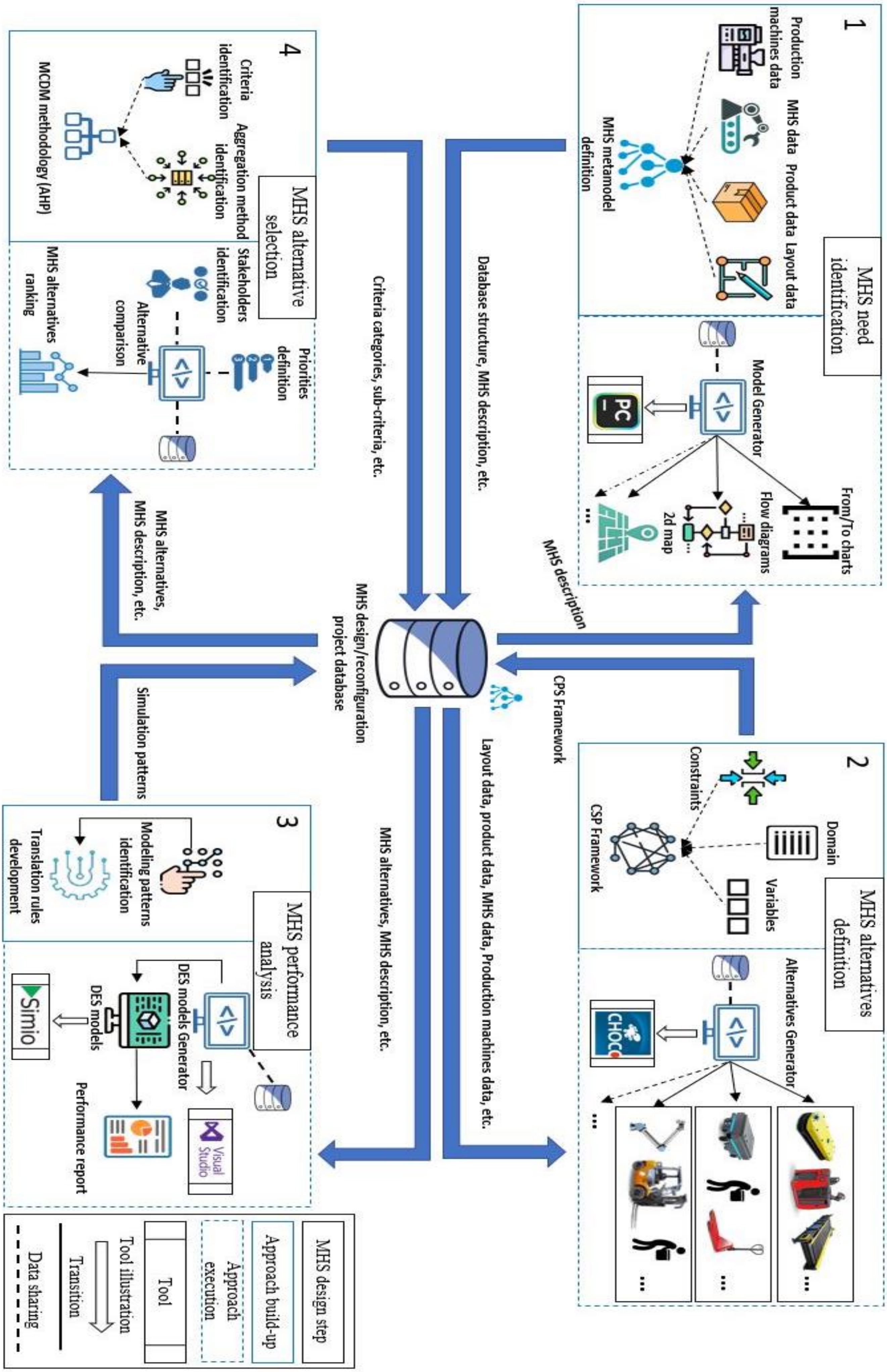

Figure 1. MHS design approach

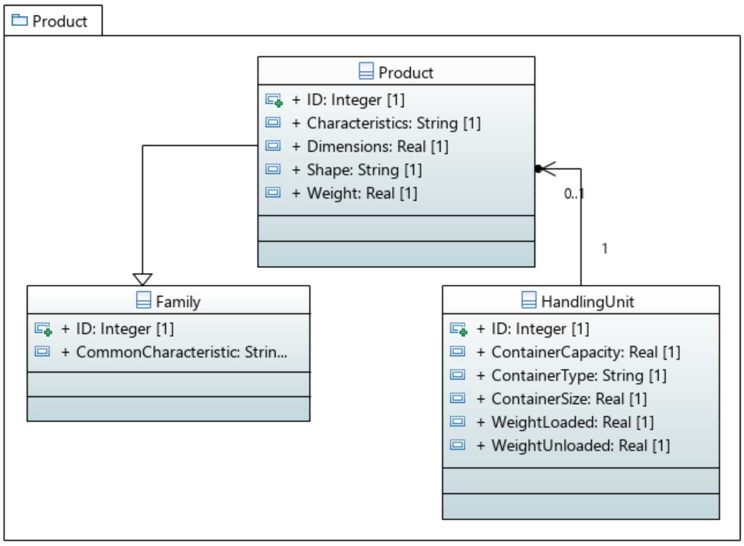

Figure 2a. Product data

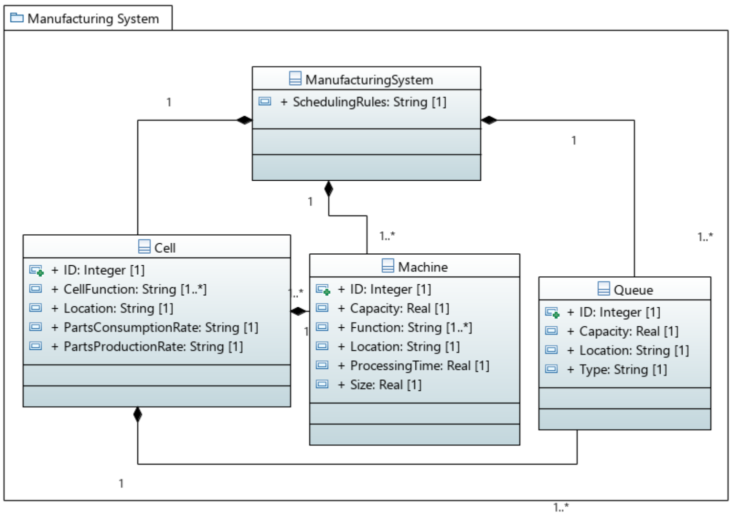

Figure 2b. Manufacturing System data

2.2 Material Handling System alternatives definition

In the literature, the MHS alternatives definition procedures are most of the time based on intuition or experts' knowledge which leads to hardly justified MHS proposal. In the developed approach, the aim is to conduct the MHS alternatives definition based on the MHS requirements (which can be retrieved from the centralized database of the MHS design/reconfiguration project). Then, based on this data, suitable MHS alternatives are to be constructed and proposed to the decision-makers. In the proposed approach, the alternative proposal is made using a CSP (Constraint Satisfaction Problem). A CSP framework defines a given problem as a set of constraints (C), which state relations between the problem's variables (V), where each variable ($v_j \in V$) can take a value only in a finite domain (D_j) (Sylla et al., 2018). In the literature, CSP can be found in different contexts such as resource reconfiguration and product configuration. For instance, in (Allibe et al., 2022) Resource Reconfiguration deals with the allocation of settings (which can be associated with tools) to different resources to manufacture a specific product family. This illustrates the use of CSP to drive the allocation process. The CSP allows to generate all the possible resource configurations based on compatibility constraints.

CSP frameworks can be adapted in the context of MHS alternatives definition, where:

- The characteristics of the layout (length of the path, the width of the path, height of the shop floor, etc.) and the handling unit (weight of the container, dimension of the container, the type of container, etc.) can be expressed as constraints (C)
- The Material Handling Operations of the system under study (such as transport, store, grab, pick, place, etc.) can be expressed as variables (V), and their characteristics (ex. intensity of the flow) are mentioned through constraints (C).
- The list of feasible Material Handling Equipment (such as Automated Guided Vehicles, Forklift, Automated Storage and Retrieval Systems, Cobots, etc.) can be expressed as a domain (D)

In this proposal, the allocation of MHE to MHO is done by selecting a value in D (set of equipment) to the MHO (members of V). Once this data is expressed through the three elements of CSP (constraints, variables, and domain), a solver off the shelf is used to obtain the alternatives (such as Choco-solver library). In order to build the toolkit for this step of the process, a bridge is developed between the database of the project and the CSP writing. The analysis of data generates the constraints (C), and variables (MHO of V). Then an analysis of the equipment catalog (that can be stored in the central database) permit to generate the domain (D). Finally, Choco-solver java library is used to generate the MHS alternatives. A detailed description of Choco-solver library can be found in (Prud'homme & Fages, 2022). The obtained set of MHS alternatives is then evaluated through the MHS selection process including a phase of performance analysis. The proposed approach for MHS alternative generation supports obtaining suitable and justified MHS proposals and helps to browse a bigger solution space than with expert judgment.

2.3 Material Handling System performance analysis

To identify the most adapted MHS alternative for a given production plant, it is important to evaluate all the alternatives through several criteria, such as costs, operational excellence, ergonomics, impact on the environment, etc. It is essential to evaluate the dynamic behavior of the MHS alternatives under different circumstances and scenarios (an increase in the production rate, machine breakdown, bottlenecks, etc.). Such analysis allows decision-makers to see the impact of each alternative on the performance of the whole manufacturing system.

However, the performance analysis of MHS is a complex task. Additionally, having several design MHS alternatives to consider increases its complexity. Numerous indicators should be handled to obtain a trustful representation of the system (such as on time deliveries within the plant, material shortages, product waiting time, etc.). These indicators can be observed using simulation-based approaches. The literature shows some concerns regarding the simulation of MHS, such as the lack of formalization of the model creation, the extensive effort and time needed for model creation (especially for large-scale companies), and the dependency on experts' knowledge for the simulation models development, etc.

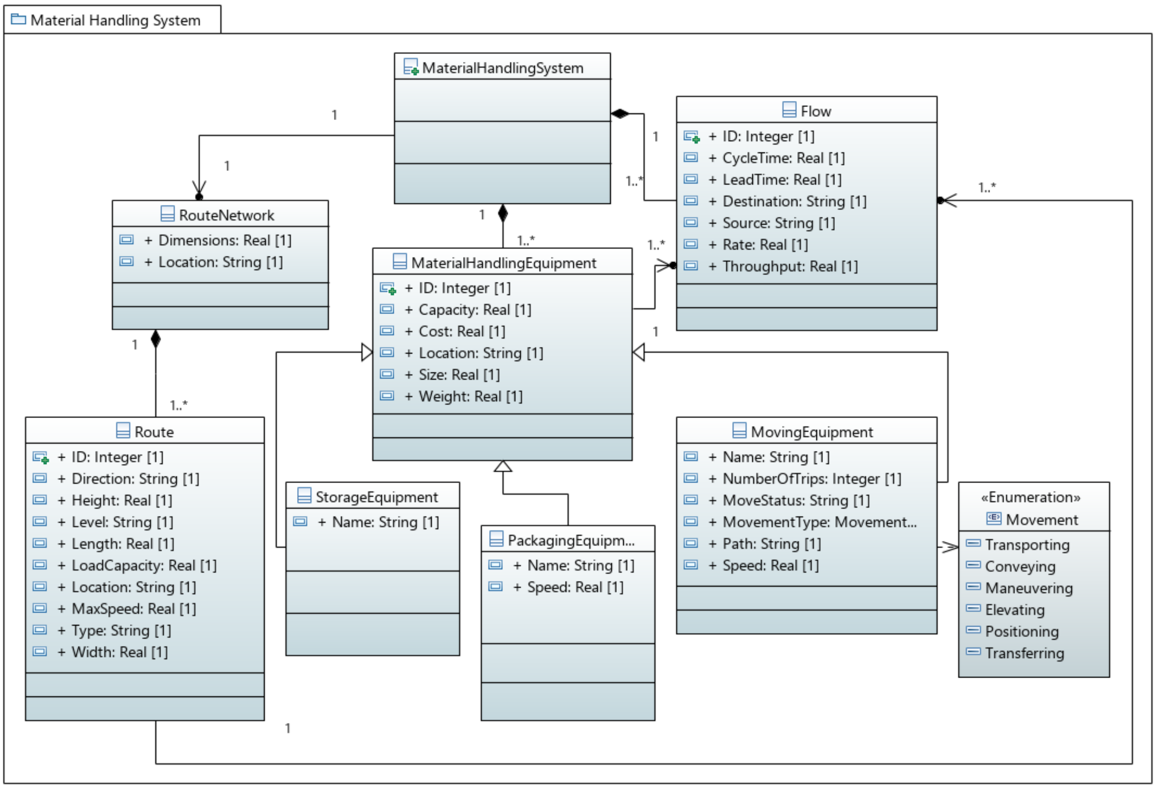

Figure 2c. Material Handling System data

To address these concerns, we proposed a DDSE combined with an MBSE approach for the generation of simulation models for MHS design. For the execution of this approach, a structured set of data describing all the elements interacting with the MHS (e.g. layout data, manufacturing system data, MHS data, and product data) is required. In the context of this paper, the data structure is implemented in the centralized database of the MHS design project (see figure 1). Afterward, modeling patterns of MHS were developed in SIMIO, and translation rules were defined and then coded from the MHS metamodel to the model patterns in SIMIO using C#. As a result, a generic, extensible, and scalable data-driven approach for MHS simulation model creation is obtained. When using this part of the approach, engineers are using the data from need analysis and alternatives creation to generate the simulation models of candidate MHS. An experimentation plan using the models is then executed to retrieve the performances of the MHS alternatives under a selected set of scenarios. For this step, several strategies can be utilized as replaying previous production periods or extrapolating future production periods. The measured KPIs are not the only decision drivers for the selection of the most suitable MHS. Therefore, these KPIs are given for the last step of the process which if the MHS selection by applying a multi-criteria decision process.

2.4 *Material Handling System alternative selection*

The step of MHS alternative selection (see bottom left part of figure 1) is the last phase of the design process. It receives important data from all the previous steps through the centralized database. It starts with the MHS need identification which gives insights about the problems and improvements to make for a given system. Then, the MHS alternatives definition phase offers a justified set of design alternatives that are not proposed intuitively. In addition, the performance analysis reports give an overview of the dynamic behavior performance of each alternative which decreases biases and supports decision-makers during their MHS alternative selection process.

The objective of the selection is to find the best alternative for a given system. To reach this result, a set of criteria has to be used to evaluate different MHS alternatives. This evaluation process can be applied using different techniques such as the analytic hierarchy process (AHP) method. It includes both qualitative and quantitative aspects (Soufi et al., 2021). It converts the problem into a hierarchical structure, where the objective is at the top level, followed by several assessment criteria. These criteria are judged over various alternatives to achieve the best solution (Agarwal & Bharti, 2018). AHP method is based on pairwise comparison matrices which can be used for measuring the importance of criteria (Saputro & Rouyendegh Babek Erdebilli, 2016), and also evaluating alternatives according to each criterion.

To conduct an accurate MHS alternative selection, it is essential to have a diversified set of criteria (e.g. economic, environmental, ergonomics, technical, etc.), and to aggregate individuals' judgments and preferences. It is relevant to include the evaluations of different stakeholders to conduct such decisions. In (Soufi et al., 2021), a consistent AHP methodology for the MHS alternative selection is proposed. It is combined with a list of criteria that might be included in an MHS selection. In this methodology, the selection is based on a list of potential criteria that were identified from the literature and industrial case studies. The proposal categorizes 61 criteria into 11 classes and aims to provide decision-makers with insights about the existing criteria and their definitions. The evaluation process is structured in two steps. First, decision-makers' preferences are identified to structure the decision. Then, the structured set of the identified criteria is used to compare alternatives. In this multi-actor decision process, a technique is provided to aggregate individuals' judgments and preferences. The literature presents several aggregation methods. Namely, the aggregation of individual priorities (AIP) procedure has been selected. It can combine the judgments while keeping the individual identities (e.g. the finance manager will have a higher priority compared to others while evaluating criteria related to economics) (Escobar et al., 2004; Forman & Peniwati, 1998). The AIP is detailed in(Dong et al., 2010). In the proposed process the set of deciders is questioned on the set of relevant criteria to be included in the decision and on their relative importance with each other. Consensus and AIP techniques are used to define the decision structure to be used for the alternatives' evaluation. Then a round of comparison of MHS alternatives is performed by the decision-makers based on the selected criteria with the support of all the data gathered during the design process (Needs analysis, performance evaluation). The procedure leads to an ordered set of MHS for the given problem. Finally, sensitivity analysis may be performed on the obtained proposal. To support the MCDM, a software prototype with Java code and Excel files has been developed.

3 THE MODULARITY OF THE APPROACH

This paper presents an MHS design approach that is composed of four main steps: MHS needs and requirements analysis, MHS alternatives definition, MHS performance analysis, and MHS alternative selection. The approach is presented as a succession of interdependent steps. The realization of each step depends on data generated through other steps (see Figure 1). However, there are still benefits from using parts of the approach. For example:

- If the objective of the study is to identify the needs of a system, the MHS needs identification step presents an RDM that generalizes MFA practices found in the literature. The RDM can be used to identify different parameters that allow a precise description of the MHS and an effective MFA. Once this data is obtained, MBSE approaches can be deployed by using a software program that generates models to view the performance of the system under study (such as flow charts, from-to charts, process flow, etc.) (Soufi et al., 2022)
- If the objective of the study is to analyze the dynamic behavior of MHS, the MHS performance analysis step is developed in a way that provides decision-makers with a formalized model where data expressing MHS needs can be gathered, analyzed, and then transformed into DES. This approach replaces the try-and-error procedures (since the models are developed based on data instead of intuition) and reduces the development time and costs of simulation models.
- If the objective of the study is to conduct an MHS selection of a predefined set of MHS alternatives, in (Soufi et al., 2021) a methodology for MHE selection is proposed. The methodology is associated with a list of 61 criteria. The objective of this list is to support and incite decision-makers to choose the appropriate criteria for the realization of the MHE/MHS selection.

Thus, parts of the design approach and their associated toolkit are still relevant separately. However, the objective of associating all the steps of the approach together is to support decision-makers with a formalized approach using a centralized data structure needed for the MBSE approach of the whole MHS design process.

4 CONCLUSION & PERSPECTIVES

The MHS design and reconfiguration problem lacks a consensus on how to address it systematically, with literature studying isolated aspects without showing their dependencies.

This paper presents a four-step approach based on Systems Engineering principles to address the MHS design problem systematically. It begins with defining the system's needs using a metamodel, followed by proposing MHS design alternatives using a CSP algorithm. The performance analysis step uses compiled data to generate simulation models, and the MHS alternative selection involves a multi-actor decision-making process guided by a methodology and a list of criteria. The approach provides stakeholders with a clear understanding of the system's needs and dynamic performance behavior of each MHS alternative.

Academic and industrial case studies were conducted to validate each step of the MHS design approach. The academic case study concerns a research and teaching Platform located at the Grenoble Institute of Technology – France. It is a small-size production system mainly used to assemble products. This case study covers a simple MHS design scenario in which it is aimed to transport different mechanical parts across the platform for assembly and quality control. Secondly, the industrial case concerns a plant of a protective equipment manufacturer, in which a variety of products (sometimes customized) are made at medium and high production rates. The productive activities are done in eleven production cells, each product family is processed in one particular cell. This case study aims to propose a new MHS to ensure enough materials for each cell for one hour of production. To address this problem, thirteen decision-makers from different backgrounds (quality control, economics, operation management, etc.) took part in the MHS design approach. As a result, satisfactory solutions were obtained and were accepted by the direction to be deployed in the plant. The results of the case studies cannot be presented here for paper length reasons.

For future work, an overall case study that addressed the whole design approach should be conducted for a final demonstration purpose. The various steps could be enhanced or challenged by other performance analysis techniques or complementary optimization techniques for alternatives creation. AI techniques could also be useful for the decision phase of the needs & requirements analysis steps.

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6 REFERENCES

Agarwal, D., & Bharti, P. S. (2018). A case study on AGV's alternatives selection problem. *International Journal of Information Technology*.

Allibe, M., Sylla, A., & Alpan, G. (2022). A generic knowledge model for resource reconfiguration in the context of reconfigurable manufacturing systems. *26th ACM International Systems and Software Product Line Conference, SPLC 2022 - Proceedings*, *B*, 217–223.

Avitabile, M. (2022). *Task assignment in material handling systems and impact of Logistics 4.0: a systematic literature review*. 2021–2022.

Beamon, B. M. (1998). Performance, reliability, and performability of material handling systems. *International Journal of Production*

Research, *36*(2), 377–393.

Bouh, M. A., & Riopel, D. (2016). Material handling equipment selection: New classifications of equipments and attributes. *Proceedings of 2015 International Conference on Industrial Engineering and Systems Management, IEEE IESM 2015*, *October*, 461–468.

Chang, K. H., Huang, Y. H., & Yang, S. P. (2014). Vehicle fleet sizing for automated material handling systems to minimize cost subject to time constraints. *IIE Transactions (Institute of Industrial Engineers)*, *46*(3), 301–312.

Choe, P., Tew, J. D., & Tong, S. (2015). Effect of cognitive automation in a material handling system on manufacturing flexibility. *International Journal of Production Economics*, *170*, 891–899.

Dong, Y., Zhang, G., Hong, W. C., & Xu, Y. (2010). Consensus models for AHP group decision making under row geometric mean prioritization method. *Decision Support Systems*, *49*(3), 281–289.

Escobar, M. T., Aguarón, J., & Moreno-Jiménez, J. M. (2004). A note on AHP group consistency for the row geometric mean priorization procedure. *European Journal of Operational Research*, *153*(2), 318–322.

Esmaeilian, B., Behdad, S., & Wang, B. (2016). The evolution and future of manufacturing: A review. *Journal of Manufacturing Systems*, *39*, 79–100.

Forman, E., & Peniwati, K. (1998). Aggregating individual judgments and priorities with the Analytic Hierarchy Process. *European Journal of Operational Research*, *108*(1), 165–169.

Forsberg, K., & Krueger, M. (2011). *A guide for system life cycle processes and activities: A guide for system life cycle processes and activities.* San Diego, CA (US): Incose.

Frohm, J., Lindström, V., Stahre, J., & Winroth, M. (2008). Levels of automation in manufacturing. *Ergonomia-an International Journal of Ergonomics and Human Factors, 30(3).*

Gaur, A. V., & Ronge, B. P. (2020). Ranking Material Handling Equipment Selection Criteria by AHP. *Techno-Societal 2018*, 175–182.

Hao, Q., & Shen, W. (2008). Implementing a hybrid simulation model for a Kanban-based material handling system. *Robotics and Computer-Integrated Manufacturing*, *24*(5), 635–646.

Hellmann, W., Marino, D., Megahed, M., Suggs, M., Borowski, J., & Negahban, A. (2019). Human , AGV or AIV ? An integrated framework for material handling system selection with real-world application in an injection molding facility. *The International Journal of Advanced Manufacturing Technology*, 101(1-4), 815-824.

Kumar, S., & Raj, T. (2016). Selection of material handling equipment for flexible manufacturing system using FAHP. *International Journal of Recent Advances in Mechanical Engineering (IJMECH)*, *5*(1), 25–45.

Lee, K. W., Chang, D. S., & Park, S. C. (2018). Material handling system modeling of a modern FAB. *ACM International Conference Proceeding Series*, 271–275.

Lindblad, L., Witzmann, M., & Vanden Bussche, S. (2018). Data-Driven Systems Engineering. Turning MBSE into Industrial Reality. *International Systems & Concurrent Engineering for Space Applications Workshop (SECESA)*, *1*, 1–3.

Longo, F., Mirabelli, G., & Papoff, E. (2005). Material flow analysis and plant lay-out optimization of a manufacturing system. *Proceedings of the Third Workshop - 2005 IEEE Intelligent Data Acquisition and Advanced Computing Systems: Technology and Applications, IDAACS 2005*, *September*, 727–731.

Meng, C., Nageshwaraniyer, S. S., Maghsoudi, A., Son, Y. J., & Dessureault, S. (2013). Data-driven modeling and simulation framework for material handling systems in coal mines. *Computers and Industrial Engineering*, *64*(3), 766–779.

Mestiri, S., & Fottner, J. (2022). Simulation-based dimensioning of internal transport systems. *Journal of Factory Economy*, *117*, 229–233.

Onut, S., Kara, S. S., & Mert, S. (2009). Selecting the suitable material handling equipment in the presence of vagueness. *International Journal of Advanced Manufacturing Technology*, *44*(7–8), 818–828.

Persson, J., & Smedberg, S. (2019). *Evaluating automation potential in a material handling environment*.

Prud'homme, C., & Fages, J.-G. (2022). Choco-solver: A Java library for constraint programming. *Journal of Open Source Software*, *7*(78), 4708.

Raman, D., Nagalingam, S. V., Gurd, B. W., & Lin, G. C. I. (2009). Quantity of material handling equipment-A queuing theory based approach. *Robotics and Computer-Integrated Manufacturing*, *25*(2), 348–357.

Saputro, T. E., Masudin, I., & Rouyendegh, B. D. (2015). A literature review on MHE selection problem: Levels, contexts, and approaches. *International Journal of Production Research*, *53*(17), 5139–5152.

Saputro, T. E., & Rouyendegh Babek Erdebilli, B. D. (2016). A hybrid approach for selecting material handling equipment in a warehouse. *International Journal of Management Science and Engineering Management*, *11*(1), 34–48.

Sendra, C., Gabarrell, X., & Vicent, T. (2007). Material flow analysis adapted to an industrial area. *Journal of Cleaner Production*, *15*(17), 1706–1715.

Soufi, Z., David, P., & Yahouni, Z. (2021). A methodology for the selection of Material Handling Equipment in manufacturing systems. *IFAC-PapersOnLine*, *54*(1), 122–127.

Soufi, Z., David, P., & Yahouni, Z. (2022). A Reference Data Model for Material Flow Analysis in the Context of Material Handling System Design and Reconfiguration. *IEEE International Conference on Industrial Engineering and Engineering Management*, *2022-Decem*, 1488–1492.

Soufi, Z., David, P., & Yahouni, Z. (2023). Challenges of Material Handling System design in the context of industry 4.0. *In Service Oriented, Holonic and Multi-Agent Manufacturing Systems for Industry of the Future: Proceedings of SOHOMA 2022*, (pp. 291-303). Cham: Springer International Publis.

Starbek, M., & Menart, D. (2000). Optimization of material flow in production. *International Journal of Machine Tools and Manufacture*, *40*(9), 1299–1310.

Stephens, M. P., & Meyers, F. E. (2013). Material Handling. In *Manufacturing facilities design and material handling*. Purdue University Press.

Stephens, M. P. (2013). Manufacturing Facilities Design & Material Handling. In *Manufacturing Facilities Design & Material Handling*.

Sylla, A., Guillon, D., Vareilles, E., Aldanondo, M., Coudert, T., & Geneste, L. (2018). Configuration knowledge modeling: How to extend configuration from assemble/make to order towards engineer to order for the bidding process. *Computers in Industry*, *99*, 29–41.

Vieira, A. A. C., Dias, L. M. S., Pereira, G. A. B., Oliveira, J. A., Do Sameiro Carvalho, M., & Martins, P. (2018). Simulation model generation for warehouse management: Case study to test different storage strategies. *International Journal of Simulation and Process Modelling*, *13*(4), 324–336.