A Reference Data Model for Material Flow Analysis in the context of Material Handling System Design and Reconfiguration

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Abstract - **The design and reconfiguration of Material Handling Systems (MHS) at the factory scale is known to be complex. Various data and analyses are required to define the internal logistics needs the MHS must fulfill. In the literature, the identification of the MHS' needs is performed through Material Flow Analysis (MFA). The MFA is expressed through charts and diagrams which are manually developed. The manual development of charts and diagrams leads to gathering data in a disseminated way. Additionally, MFA is differently addressed in the literature; each work analyzes a different and restrained set of data. In this paper, we aim to generalize MFA by proposing a Reference Data Model (RDM) using UML (Unified Modeling Language) class diagrams. It allows listing and structuring all the data required for the MFA. The RDM can be used to conduct a data-driven MFA which enables data integrity and the reduction of the development time of charts and diagrams. A proof of concept is also given to show the ability to simultaneously generate charts and diagrams, while ensuring data integrity.**

Keywords - **Manufacturing Systems, Material Handling Systems, Material Flow Analysis, Reference Data Model.**

1. INTRODUCTION

Material Handling Systems (MHS) address storing, packaging, and moving products. It plays a key role in the performance of the entire manufacturing system [1]. An efficiently designed MHS leads to effective production management, improvement of on-time delivery, and enhancement of production quality [2]. The design of modern manufacturing systems can be very complex and the resulting system can be a source of excessive expenditure if it is not efficiently designed [3]. In such design processes, many dimensions should be integrated as the dynamic behavior of the system, information systems, materials, the interaction between operators and machines, etc. In this work, MHS is seen as the interaction between Material Handling Equipment (MHE) and operators within the manufacturing system. All the elements constituting the MHS must function as a whole to meet the required system objectives [4].

Before proceeding to the design and reconfiguration of such systems, a tremendous amount of data is needed to take the appropriate design decisions (e.g. deciding the level of automation of Material Handling Activities, selecting the set of MHE, etc.) [4]–[6]. As in any systems engineering process, the efficiency of the MHS design process depends on the correct identification and understanding of the needs and requirements. For MHS design, the needs analysis is usually done through the Material Flow Analysis (MFA). In the literature, MFA is considered to be the first step of the MHS design and reconfiguration [7]. It is defined as the systematic assessment of flows and stocks of materials within a system defined in space and time.

In the literature, MFA is addressed in various ways in terms of the targeted data. For instance, in [8] the authors focus on the analysis of the paths that are taken by different family parts to perform the MFA. While in [9] other aspects are analyzed, such as the product's characteristics and dimensions. However, it can be seen that in the literature the MFA is not unified, but the different addressed concepts should be related to one another. Additionally, the existing MFA techniques mainly consist of manually executed procedures such as building charts and diagrams [10] (E.g. From-To charts, Material flow diagrams, Spaghetti diagrams, etc.). These manual approaches can suffer from several drawbacks, especially in a large-scale manufacturing system; different MFA charts and diagrams have to be developed separately to describe the MHS' needs without digitization nor ensuring data integrity. Thus, a proposition may be formulated to unify and generalize the MFA practices to make them compatible and complete. A basis to generalize MFA would be to propose a Reference Data Model (RDM) to clarify what data should be considered in an MFA and how they are articulated. Moreover, the proposal of an RDM opens the path to a data-driven MFA. Data-driven approaches allow providing services for MFA such as charts and diagrams generation while reducing the development time and ensuring data integrity. In the work of [11], the authors proposed a data-driven approach to collect data related to the MHS of coal mines and to generate simulation models. This work shows the benefits of a data-driven approach such as; the automatic generation of simulation models, the reduction of model development cost and time, and the replicability of the analysis approach to similar systems. The main drawback of the RDM proposed in [11] is that it is specialized for a limited type of MHS (coal mines MHS).

The contribution of this paper is to propose an RDM to generalize and unify the data manipulated in MFA. To propose a relevant RDM, data are identified and selected from the current practices of MFA reported in the literature. The RDM is represented in UML (Unified Modeling Language) class diagrams. The ability to exploit the RDM in a data-

driven MFA process is demonstrated with proof of concept examples of MFA views generation.
The remaining of this paper is organized as follows; It starts with a literature review on Material Flow Analysis and Data-driven approaches. Afterward, in the 3rd section, an RDM for MFA is proposed and an application example is given. Finally, the conclusions and perspectives are given in the last sections.

2. STATE OF THE ART

2.1 Material Flow Analysis

In the industrial area, the literature shows that articles use the MFA to examine the movement of the material over time [6]. It can be used to analyze the whole supply chain [8, 12], or it can focus on the analysis of MHS [6, 13, 14]. The steps of MFA may vary depending on the objective of the analysis. For example, it can be used for; optimization purposes [8], waste management [12], simplification of the material flows in the facility [6], or for the plant layout design [9]. However, data collection remains a common step.
In the context of MHS design, MFA is mainly conducted through manual procedures such as charts and diagrams. These graphical representations help to gather relevant data for MHS design, for example;

- Production sheet [9]: it allows the collection of data relatively to each phase of the manufacturing process.
- Working sheet [9]: it gives the possibility to compare foreseen values (production time and quantity) with real values.
- Flow chart [10]: it allows to study of the material flow of each product family (see figure 3).
- Process flow layout [10]: It allows to identify the existing flow path on a layout for the products made by the company (see figure 5).
- From-to chart [10]: it displays the flow of material between functional areas of a plant based on a specific handling unit (see figure 4).

The articles addressing the MFA, in the context of MHS design and reconfiguration, usually focus on a restrained set of data. For example, in [12, 14] the authors only use flow charts to perform the MFA. While in [10] the authors focus on other charts and diagrams, such as string diagrams and from-to charts These manual procedures are time-consuming and difficult to exploit; Having different charts and diagrams that are separately developed without data centralization does not ensure data integrity. In the literature, RDMs are used to adapt data-driven approaches. It allows better exploitation of data by giving the possibility to centralize data, thus, ensuring data integrity. An opportunity is to provide an RDM covering the various MFA practices and allowing a robust data utilization.

2.2 Data-driven approaches

With the latest information and computing technology innovations, new opportunities can be identified for MFA, such as data-driven approaches. It helps to develop models to describe systems with similar features and functionalities [10-15]. It can be adapted to support the design and operational decision-making in MHS [16]. The most popular language for such approaches is UML (Unified Modeling Language). It is mostly used for describing a data-capturing operation [16].
In [11], the authors propose data-driven modeling and simulation based on an RDM. However, the proposed RDM can not be considered a generic model for MFA in the context of MHS; It focuses on the simulation of the equipment and the processes in coal mines. The information model in this work describes the data requirements for the construction and execution of a simulation model; Necessary data is retrieved following a specific data format. To reach the final result of this work, system specifications in coal mines had to be listed; MHS components, processes, and flows are represented in flow charts. Later on, UML classes are progressively constructed to represent the different aspects that were shown in the flow chart. Such approaches give the possibility to realize model transformation while ensuring data integrity. The model transformation enhances the benefits of proposing an RDM for the generalization of MFA; It allows to describe and understand the system by generating different charts and diagrams simultaneously while ensuring data integrity. This proposition would reduce the costs, time, and errors that are derived from the manual procedures that are used in the literature.
In this article, we aim to propose an RDM to conduct the MFA in the context of MHS; This generic model would allow users to describe the MHS needs of different industrial cases. Further descriptions are presented in the following section.

3. REFERENCE DATA MODEL FOR MATERIAL FLOW ANALYSIS

In the following sub-sections, before proposing our model, the literature is analyzed to derive a list of parameters that must be represented in the RDM. The goal is to define a wide range generic data structure encompassing the previous works on MFA

3.1 Data definition

The development of an RDM requires a consolidated list of parameters. In our case, parameters are needed to describe the different parts and interactions that can be found in MFA in the context of MHS design and reconfiguration. These elements allow the creation of an MFA meta-model that will support the analysis.
The literature is analyzed to propose an RDM covering the existing practices of MFA. Articles were selected based on the journal's ranking, the number of citations, and compliance with the topic (MFA in the context of MHS design and reconfiguration).

MFA in the context of MHS is not a common subject in the literature, despite its importance to express the MHS' needs. Thus, the data identification is not only made on papers that address the MFA only but also on papers that discuss MHS issues in general. As a result, twenty-two articles were selected and only twelve are retained due to the redundancy in the mentioned data [2, 6, 21, 22, 9, 10, 14, 16–20]. The analysis led to the identification of 197 parameters grouped into 42 categories (such as machine data, product data, flow data, etc.). Afterward, a correlation analysis was conducted to reduce the list of parameters by keeping the generic ones and removing the parameters addressing the same concept (for example; aisle, corridor, and alley can be combined in the concept of route). As a result, a list of 59 parameters is selected and grouped into three main data categories; Product features, Material Handling System, and Manufacturing System.

3.2 *Data structuring using class diagram*

Once the data labels (parameters) are identified, UML classes are used to provide a view of the RDM for MFA. The top-level data is presented in figure 2a. This MFA class is a composition of three main classes represented in different packages:

- Product (figure 2b): This package is composed of three classes; Product class, Family class, and Handling Unit class. the parameters of this class help to describe the features of a given product. Each product belongs to a specific product family and might be handled in a specific container. That is why the Product class is linked to two other classes; Handling Unit, and Family.

- Manufacturing System (figure 2c): this data category focuses on components of the manufacturing system; It starts with the description of the cell class, and just like the real manufacturing systems, the cell class is a composition of two other classes; Machine and Queue.

- MHS (figure 2d): this package describes two main aspects; The layout of the shop-floor (through Route Network and Route classes). And the characteristics of the MHS. The MHS class is composed of the three categories of MHE (moving equipment, packaging equipment, and storage equipment). The separation of these categories allows a better description of each class, for example, it can be seen that the moving equipment requires more parameters than the other MHE categories. Moreover, the performance of MHS can be expressed through the Flow class.

This RDM summarizes the different data that are needed to generalize the data that may be part of MFA. Besides, the RDM can be exploited using a data-driven approach to facilitate the MFA. The following section shows a demonstrator of a data-driven MFA used in a real case study.

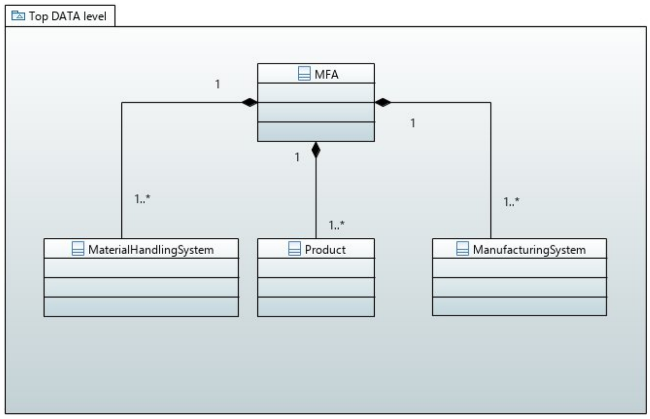

Figure 2a. Top data level

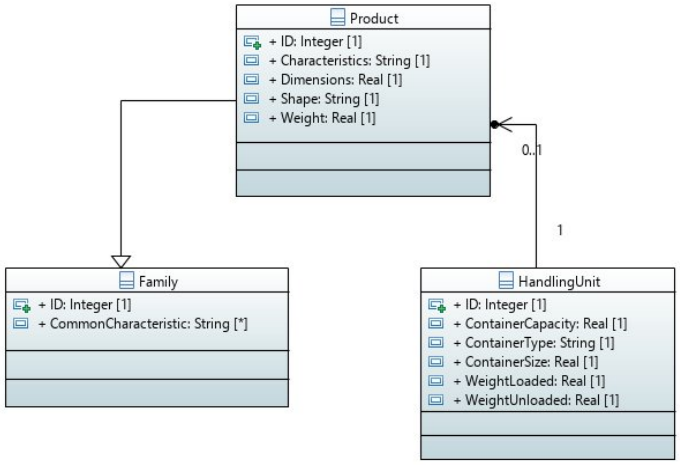

Figure 2b. Product package

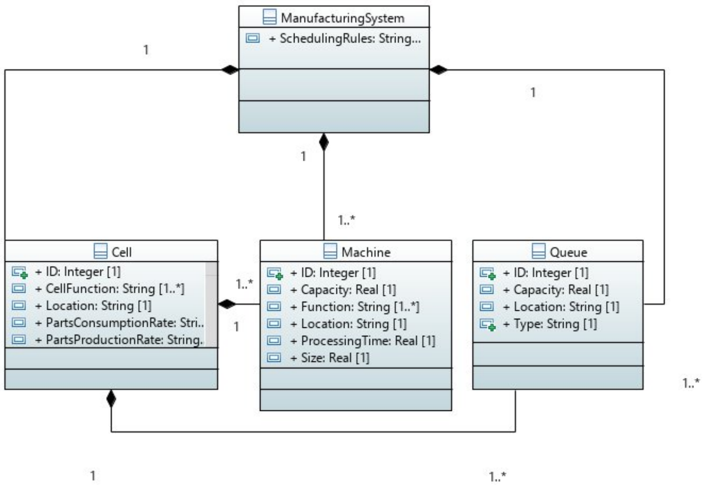

Figure 2c. Manufacturing System package

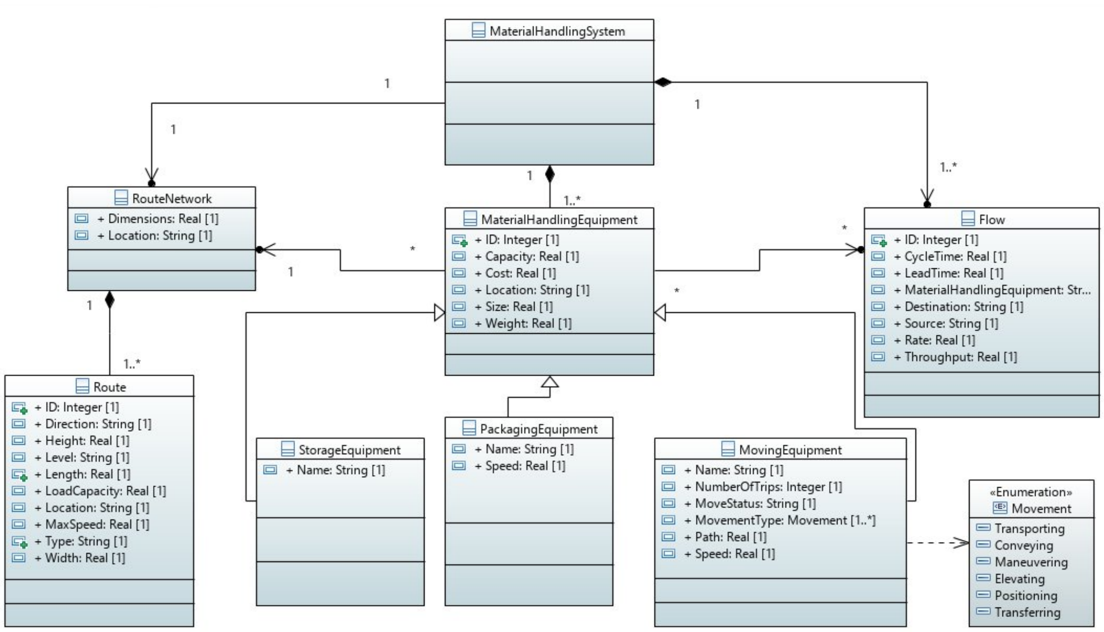

Figure 2d. Material Handling System package

3.3 *Application example*

To demonstrate the use of our proposal, a real case study was conducted to perform the data-driven MFA. The case concerns a plant of safety equipment manufacturer (climbing gear, caving gear and work-at-heigh equipment). The shop-floor is composed of 21 production machines arranged in five production cells.

To proceed to the data-driven MFA, the RDM was first implemented on an online database management system. Then, the users filled the data needed for the MFA in the database. Afterward, the data was extracted using a software program that we developed. Finally, different MFA charts and diagrams were simultaneously generated while ensuring data integrity, some examples can be seen in figures 3, 4, and 5.

- The flow chart (see figure 3) was generated to identify the path of the three product types.
- The from-to chart (see figure 4) was used to display the number of containers moved between the five production cells per week.
- The process flow (see figure 5) layout was used to represent the layout of the shop-floor.

five The-shop floor is composed of 21 production machines arranged in five production cells. The shop-floor produces three The user starts first by filing the database following the RDM that we proposed in figures 2a, 2b, 2c, and 2d. The

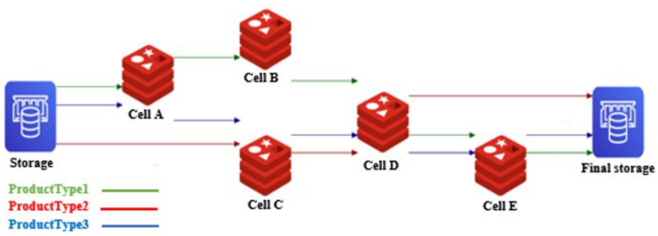

Figure 3. Flow chart of the three types of product

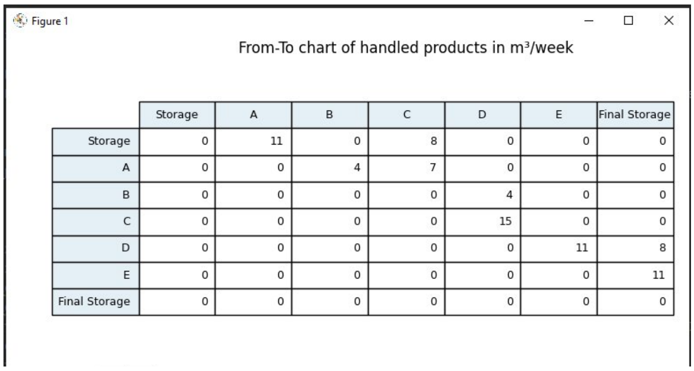
Figure 1

From-To chart of handled products in m³/week

	Storage	A	B	C	D	E	Final Storage
Storage	0	11	0	8	0	0	0
A	0	0	4	7	0	0	0
B	0	0	0	0	4	0	0
C	0	0	0	0	15	0	0
D	0	0	0	0	0	11	8
E	0	0	0	0	0	0	11
Final Storage	0	0	0	0	0	0	0

Figure 4. From/To chart of the handled containers/week between the 5 production cells

4. DISCUSSION AND CONCLUSION

Before the design or reconfiguration of the MHS, it is important to define the MHS' needs to take the appropriate decisions. In the literature, the MHS' needs are expressed by performing the MFA. The MFA is considered to be the beginning of any MHS design and reconfiguration processes. Yet, the conduction of the MFA is performed with a restrained set of data and is mainly done through error-prone and time-consuming manual procedures. This opens up a new opportunity to propose an RDM to express the data needed for the MFA in the context of the MHS design and reconfiguration.

The goal of this paper is to propose an RDM to generalize the MFA in the context of MHS. The RDM regroups different parameters that allow a precise description of MHS and an effective MFA; The proposed data structure gives the ability to adopt a data-driven MFA that can generate simultaneously different MFA charts and diagrams while reducing the

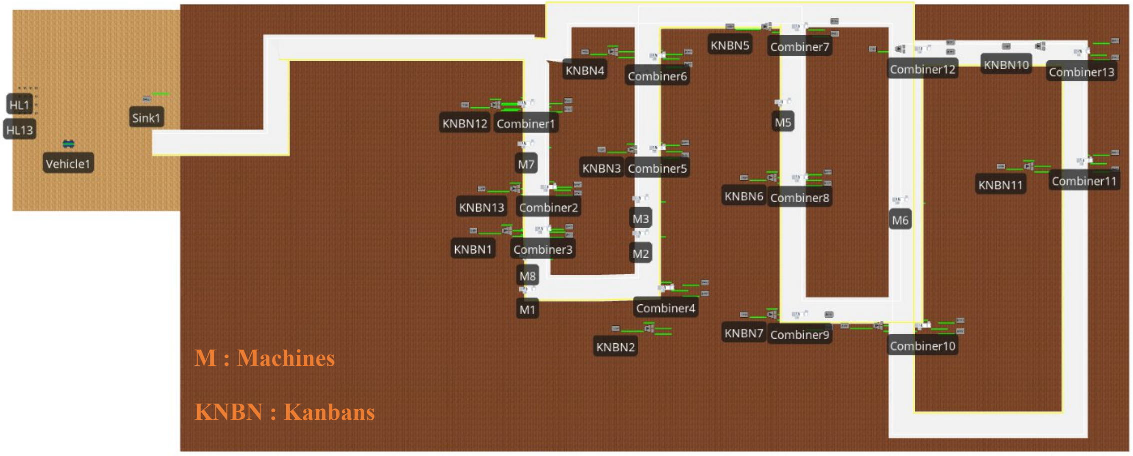

Figure 5. Process flow layout

development time, costs, and errors by ensuring data integrity. A proof of concept for data-driven MFA is given in a case study

To propose a consistent RDM, 197 parameters were identified from 12 articles. Later on, 57 parameters were selected using correlation analysis to remove the redundancies and keep the relevant parameters. As a result, four data packages are selected to structure the data; Top data package, Manufacturing System package, MHS package, and Product package.

For future development, an MFA toolset can be created to generate automatically other MFA charts and diagrams based on the collected set of data. The automatic generation of such models would help to adapt to the new visualization needs in a short amount of time and with fewer costs. Furthermore, the proposed RDM is also exploited in another work to propose a generic, scalable, extensible, and data-driven simulation model. In this work, the automatic generation of the simulation allows the analysis of the performance of the MHS and the design alternatives. The obtained results are the subject of a submission to a journal.

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