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Abstract

Sustainability in manufacturing operations has become the subject of increasing attention in the recent years. At the operational level, knowledge about material and energy flows circulating in the production system provides information regarding costs, efficiency and environmental impact, as well as opportunities for improvements. Several methods have been proposed for flow assessment and flow cartography, but work combining production scheduling and flow assessment remains scarce. To address this issue, we propose comprehensive guidelines in order to identify waste reduction opportunities and integrate them in a scheduling problem. This work combines sustainable production principles with environmental and material flow assessment to promote waste prevention at the operational level of production, by identifying the main waste-generating activities that can be improved through scheduling. From a decision-maker's point of view, more informed choices can be made regarding the production scheduling and the opportunities for operational improvement. From a research perspective, a framework for the identification and

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integration of waste-minimizing opportunities in scheduling problems is proposed. Four steps permit the product system definition, flow inventory, economic and environmental impact assessment and scheduling problem identification. An application to a hub-cap production system serves to highlight the benefits of this methodology, showing that hazardous waste generation could be reduced by 10% using adequate scheduling.
Keywords: Waste minimization, Flow control, Environmental and cost assessment, Scheduling, Manufacturing

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Acronyms: ABC - Activity Based Costing ; ABEC - Activity Based Environmental Costing ; EAM - Environmental Activity Management ; EMA - Environmental Management Accounting ; FU - Functional Unit ; GA - Genetic Algorithm ; ITO - Input Throughput Output ; LCA - Life Cycle Assessment ; MEW-PFM - Material, Energy and Waste Process Flow Modeling ; MFA - Material Flow Accounting ; MFAM - Material Flow Assessment in Manufacturing ; MFCA - Material Flow Cost Accounting ; MFN - Material Flow Network ; MILP - Mixed Integer Linear Programming ; MIOT - Monetary Input Output Table ; PIOT - Physical Input Output Table ; QHSE - Quality, Health, Safety and Environment ; VSM - Value Stream Mapping ; WFM - Waste Flow Mapping.

Wordcount : 11393

1. Introduction

In the arising context of resource scarceness and environmental issues, new tools are being developed in order to promote greener manufacturing methods and mitigate the impacts of industrial production. Industrial companies (including the building industry) were responsible for around 83% of the world's solid waste production in 2011 (Song et al., 2015). The waste hierarchy advocated by the European parliament (European parliament, 2008) promotes the prevention, reuse and recycling – in this order – of waste as the most efficient management techniques to reduce industrial waste. From an environmental standpoint, prevention makes the most sense as it reduces resource and energy consumption, harmful emissions as well as the need for expensive waste treatment plants. It is also economically viable as it enables savings on material, production and waste management costs and can improve brand image as well as facilitate compliance with regulations. While the environmental benefit of reducing waste generation is broadly acknowledged by industrial companies, imprecise accounting makes it hard for industrialists to truly grasp its economic potential (Jasch, 2008).

To promote the reduction of industrial waste generation, we propose an approach based on operations scheduling, which "deals with the allocation of resources to tasks over given time periods and its goal is to optimize one or more objectives", i.e. operations sequencing and machine assignment (Pinedo, 2008). "Sustainable scheduling" refers to the design of production schedules that reduce environmental impact. One of the advantages of sustainable scheduling is that it does not require large investments, and can be implemented and updated on relatively short timescales. While this topic has been investigated for several years, researchers have been focusing on reducing energy consumption, and waste-minimizing scheduling has remained largely ignored. To facilitate the emergence of waste-minimizing scheduling in both industrial companies and academia, we study the links between waste generation and operations scheduling in order to:

- Identify waste prevention opportunities through scheduling in a production system;
- Estimate potential gains regarding both the environmental and economic aspects;
- Provide a scheduling problem description which includes waste minimization in its objective function.

To study these links, we choose to focus on flow assessment, or the study of how resource flows (be they materials or energy) circulate within a production system and how they are consumed at the operational level. Flow assessment is particularly relevant to our case since it has the ability to track waste flows and their characteristics, as well as include operational information in the flow description, and especially scheduling related information.

From a decision-maker's perspective, knowledge regarding the cost and environmental impacts of the various flows is important in order to consider trade-offs, especially since the real cost of waste flows tends to be severely underestimated (ADEME, 2016). From a research perspective, solving shop-floor scheduling problems has traditionally been done bearing only economic objectives in mind, such as the makespan or lateness (Giret et al., 2015) – for more information on scheduling problems involving waste minimization, see Le Hesran et al. (2019a). Providing environmental information linked to operational parameters would facilitate the integration of environmental aspects into the objective functions when modeling scheduling problems, taking advantage of the growth of multi-objective optimization in recent years.

Several methodologies exist for flow assessment (Jasch, 2003), involving economic or environmental criteria. They can be used at different decision levels, i.e. the operational, tactical and strategic ones, although they tend to be ill-adapted to improving production scheduling (Gould et al., 2016). To address this research gap, we first review the existing methodologies for flow assessment, then propose a new framework which includes economic and environmental criteria, while simultaneously focusing on the operational level of production. By incorporating parameters related to schedule efficiency into the quantitative and qualitative flow assessment, we mean for this methodology to facilitate the rapid identification, assessment and improvement of waste-related issues in scheduling manufacturing processes. Combining principles of sustainable production with material flow assessment and scheduling, this work focuses on the following research question: how can flow assessment support the identification and characterization of waste-minimizing shop-floor scheduling problems? In this paper, we provide a new framework and guidelines for the identification of waste-minimizing scheduling problems using flow assessment. By focusing on a topic that has remained largely unnoticed by researchers, we aim at providing new possibilities for industrialists to reduce their waste generation. Additionally, the dual consideration of both environmental and economic aspects and the possible tradeoffs it provides should work as an incentive for companies to implement new measures.

In the next section, an overview of the current literature on flow assessment is done, and the advantages and shortcomings of existing methodologies are identified. Based on the gathered information, we define the specifications needed for our proposed methodology to answer our research question, and a framework for its implementation is proposed in Section 3. A practical case is studied in Section 4 followed by discussion, and conclusions are drawn in the last section.

2. Literature review and positioning

In this section, the current literature regarding flow assessment and activity characterization is reviewed, especially at the operational level. As this study focuses on material flow assessment and waste-minimizing scheduling, the combination of the following keywords was used during the literature search: material, flow, modeling and waste. Terms referring to urban waste collection and management were excluded: municipal; national; regional. The Web Of Science search engine was used to identify peer-reviewed articles featuring the aforementioned combination of keywords in their title, abstract and keywords. All articles resulting from this literature search were screened to check whether they belong to our scope, and the ones deemed most relevant selected. Further research was made by looking at the references and methodologies cited in the selected papers as well as the articles citing our sampled papers. This review has focused specifically on studies published in the English language. One way to enrich it might be to consider articles written in German or Japanese, as these two countries have been at the forefront of research on material flow assessment. In addition to their consideration of environmental and economic criteria, the reviewed studies have been grouped according to the decision level they consider in their methodology, respectively the strategic and tactical (i.e.

referring to mid and long term decisions or investments) and operational (i.e. short term decisions and production planning) levels. Figure 1 shows the structure of the following subsections based on the decision level and criteria considered in the reviewed methodologies.

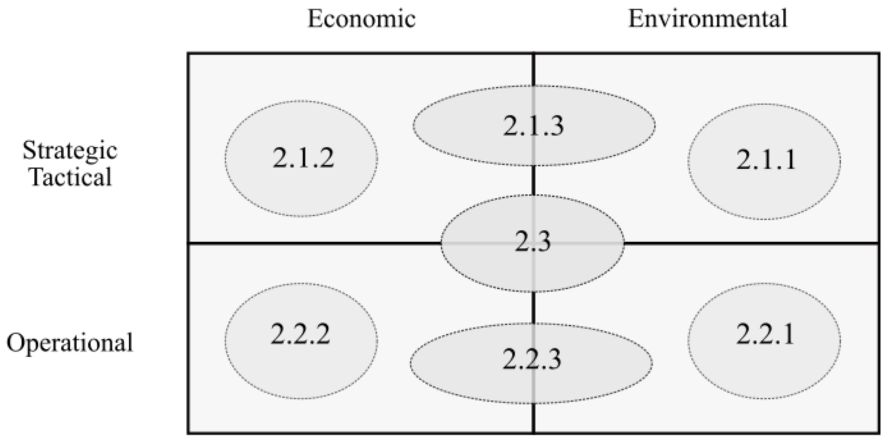

Figure 1: Content of the literature review sections based on decision level and criteria

2.1. Strategico-tactical approaches

Most applications of material flow assessment methods take place at the strategic and tactical levels of decision-making. They can cover production sites, regions or even national economies, and often provide information regarding possible investments or process improvements that can increase resource efficiency. While they are usually not suited for improving production scheduling, they can provide insight regarding data collection, environmental indicators or cost assessment. In the following paragraphs, the reviewed methodologies are grouped into three categories depending on whether they include environmental, economic or both environmental and economic criteria.

2.1.1. Environmental criteria

Environmental Management Accounting (EMA) is a framework first developed in Germany, and later formalized internationally (United Nations Division for Sustainable Development, 2001). Its aims are the identification, collection, analysis and use of information regarding material and energy flows within a system as well as their related costs and environmental impacts (ISO 14051, 2011). In most organizations, production and product pricing is done based on general accounting, which is destined to stakeholders and financial regulators. This leads to a dilution of information, with certain environmental costs (e.g. waste related costs) being included in broader categories, hence a loss of visibility regarding potential savings (Jasch, 2003). EMA aims at solving this issue by proposing a combined approach between flow assessment, general and analytical accounting. It uses metrics that are both physical (for flows) and monetary (for costs, revenues and savings), and can be used for the performance assessment of a system or the evaluation of environmental projects. Within the EMA framework, several tools are proposed to improve environmental performance. One of those is Material Flow Analysis (MFA), which aims at identifying the various material flows circulating within a system in order to detect possible inefficiencies. It is based on the principle of material balance, which states that material flows entering a quantity center eventually leave it under the form of either product or material loss. MFA is useful for figuring out where inefficiencies in resource consumption happen, providing the decision-maker with a map of flows in the system. By reducing resource consumption, it is possible to reduce the environmental impact. MFA is mostly used on large scales, such as the regional and national ones (Patrício et al., 2015) or across whole industries (Wang et al., 2016).

Life Cycle Assessment (LCA) is defined by the ISO 14040 (2006) as "a technique for assessing the environmental aspects and potential impacts associated with a product", based on its whole life cycle from raw materials extraction to end-of-life. LCA provides a comprehensive environmental assessment of products and material flows, with existing databases describing the impact of materials and processes for multiple criteria such as resource depletion, effects on human health or on the ecosystem. As it is much more specific than other methods, LCA is often used in complement with other EMA methods in order to provide comprehensive environmental information. Its applications are mostly focused on strategic planning, scenario comparison and product development and improvement (ISO 14040, 2006).

2.1.2. Economic criteria

Activity Based Costing (ABC) aims at accurately reflecting the costs of each activity performed in an organization. It is based on traditional cost accounting techniques, with two main purposes. The first one is to prevent cost distortion, which occurs when multiple costs (such as waste costs) are grouped into overhead, losing the respective source of each cost. The second purpose is to prevent non value-added activities by avoiding inefficiencies in production (Ishter and Akram, 2015). Activity Based Environmental Costing (ABEC) follows the same principles as ABC, but assigns the costs of all environmental activities to their corresponding products. This allows product costs to truly reflect their environmental costs instead of being allocated to overheads. While ABEC is shown to improve environmental performance when implemented, especially regarding resource usage, results show low adoption rates (Phan et al., 2018). Its primary focus is on the accurate cost assessment of activities, which include environmental activities, and environmental impact reduction comes as a consequence of considering environmental costs.

Viere et al. (2010) propose a Verbund-Model (or network model) based on Petri nets for scenario comparison. They use Petri net components, transitions (i.e. transformation and transportation processes), places (i.e. storage) and arrows (i.e. connections between places and transitions) to model the production system, and flows are represented as Sankey diagrams (Schmidt, 2008). Costs are assigned to flows based on the results provided by the material flow network. Implemented in a chemical company, the Verbund-Model is used to create scenarios of future demand, prices or production parameters. The authors report use in strategic planning such as forecasts regarding shortages or surpluses of materials on several years or identification of projects to avoid future issues.

2.1.3. Environmental and economic criteria

As an extension of MFA, Material Flow Cost Accounting (MFCA) is one of the main tools within the EMA framework for flow assessment. It is defined as a "tool for quantifying the flows and stocks of materials in processes or production lines in both physical and monetary units" (ISO 14051, 2011). MFCA's main goal is a better knowledge of the nature and costs of material flows and energy use in order to support decision-making in production and improve the environmental and financial performances. Similarly to MFA, it is based on the material balance principle within a system, but adds the cost of each flow to the information provided. By observing which flows represent the biggest impact or cost, it becomes possible to identify inefficiencies in the system and propose improvement measures. These measures tend to focus on process improvement or product and plant design (Wang et al., 2017), although some cases of efficiency improvement through lot-size are proposed by Zhao et al. (2013). More detailed information on the MFCA process is available in ISO 14051 (2011). While the introduction of the ISO 14051 standard might facilitate its adoption in industrial companies, research has so far concentrated on the implementation process of MFCA within a company rather than on extending potential applications, especially to the operational level.

Propositions have been made to improve the applicability of MFCA, such as Schmidt (2013) who propose an extension of MFCA (Ext-MFCA) that adds environmental information to each flow besides physical and economic data. Using mathematical equations, each flow is linked to its corresponding greenhouse gases emission equivalent. This permits to easily switch between physical, economical and environmental representations. This information provides new insight for the decision-maker, since the physical and environmental dimensions are not necessarily correlated (i.e. a flow with a high impact on physical metrics might not have a high environmental impact, and conversely). Schmidt et al. (2015) improve energy flow modeling in MFCA to provide more accurate information on energy consumption and cost estimation.

The Extended Activity Based Environmental Costing (ExtABEC) method is described in Cagno et al. (2012), which considers not only the products but also by-products and wastes as cost objects, in a similar approach to MFCA. A 12 step methodology is proposed, with a set of four cost indices to evaluate the production efficiency. Their method is implemented in an Italian company where they estimate that waste contribute for 8% of the cost of a product.

Study of material flows is also present in the building industry, which is the main waste producer in volume (Llatas, 2011). In this specific case, material flows and their resulting waste flows are usually calculated predictively in order to organize the construction or destruction plan to minimize their impact, as well as estimate their costs. In Li et al. (2016), a Work Breakdown Structure is used to determine each individual component of the construction plan, and waste-conversion indices serve to calculate their respective waste flow based on their materials requirements.

On a larger scale, Input-Output tables enable monitoring of flows at the level of national economies or industrial sectors. The Physical Input-Output Table (PIOT) is a variant of the Monetary Input-Output Table (MIOT). PIOTs share a lot of similarities with the MFA methodology (Nakamura et al., 2007), although waste tends to be overlooked, for which a first solution was proposed in Nakamura and Kondo (2002) and examplified in Nakamura and Nakajima (2005). They rely on a matrix representation of inputs (at varying degrees of processing) and processes in order to calculate the different flows, and conversions can be made from MIOT to PIOT for both economic and environmental assessments. A framework for constructing PIOTs with environmental criteria is proposed in Hoekstra and van den Bergh (2006).

2.2. Operational approaches

While strategic and tactical approaches mostly focus on the flows themselves, operational approaches tend to consider the processing units and their characteristics in the system description. This is particularly relevant to our research question, since waste-minimizing scheduling concerns primarily originate from the processes.

2.2.1. Environmental criteria

Gould and Colwill (2015) propose a new framework for Material Flow Assessment in Manufacturing (MFAM). In their five-step methodology, the authors first define the production system scope, carry out the material flow inventory and assessment, then propose an improvement scenario, an interpretation phase being applied during the whole process. They identify three manufacturing processes that can affect material flows, namely transformation, storage and transport. Transformation processes can have environmental and economic impacts on the various flows, while the storage and transportation steps are mostly related to scheduling considerations. After the flow inventory and assessment step, the authors propose to model improvement scenarios, where factors such as process sequencing, process substitution or process optimization are investigated. This step is supposed to be iterative, as each measure taken might introduce additional problems. This framework is implemented in Gould et al. (2016) in the case of two production lines with five processes each and more than 1000 products using over 1000 raw materials. Based on the first three steps, the cleaning operations associated with product changeover are deemed the most impacting, and the improvement scenario aims at minimizing the resource consumption from these changeovers. To this end, a Genetic Algorithm (GA) is proposed and compared with a comprehensive search method, and results show that the GA is more suited for instances with more than nine products. In Gould et al. (2017), the same production system is considered but the system scope is reduced to a single process responsible for the resource intensive changeovers. Improvement scenarios with process design changes are modeled and tested using k-means clustering and ant colony optimization, providing the most efficient scenario regarding resource usage and process design changes. The authors conclude on future extensions for this study, such as improving the MFAM methodology to include order quantities and fulfillment requirement, or adding flexibility to their algorithm to accommodate rescheduling. The inclusion of cost considerations is also important, especially in the case of process design changes where retrofitting is needed. The addition of multi-parameter assessment (to balance water, energy and materials consumption) will also be a future focus. This methodology enables the decision-maker to focus on the most impacting issues and implement improvement measures accordingly. It is a generic method, and while it can lead to changes on scheduling, it does not provide information regarding costs and the economical aspect of the improvement scenarios.

2.2.2. Economic criteria

The Input-Throughput-Output (ITO) method (Schubert et al., 2011) aims at gathering information on processes at the operational level. At the core of the ITO method is the flexibility of the information it can process regarding input, throughput and output. While the EMA framework focuses on costs and material flows, the ITO method aims at characterizing activities based on their operating parameters. In addition to physical flows that enter and exit an activity, information related to its operation is also included. Machining parameters or geometrical characteristics are gathered, which allows for a parametric description of the process (or at least its aspects pertaining to improving efficiency). This is particularly relevant for our research question, as the modeling of a production system requires obtaining the different parameters that affect it; in our case information regarding scheduling issues. Using parametrization, it also becomes possible to model the output flows of an activity based on its input characteristics and operating parameters. If this process is extended to the whole system, it allows for a characterization of all flows based on the characteristics of the raw materials used and the processes they go through.

Value Stream Mapping (VSM) is a lean management method that aims at identifying all non value-added activities along a production or supply, for the improvement of economic performance – e.g. reducing waiting times, inventory or overproduction. See Rother and Shook (2003) for a detailed explanation of VSM implementation. It is based on the description of all consecutive production processes, including storage and transportation. VSM provides a current-state mapping of all operations and the transitions between them, with operational information such as processing and setup times or inventory space. Based on the current-state map and identified non value-added activities, a future-state map is devised to assess the possible improvements resulting from implementing lean measures. While VSM does include material flows in its mapping, those flows mostly concern products and parts used rather than physical quantities of materials. Although the term "waste" is commonly used in VSM, it typically represents non value added activities rather than material waste.

2.2.3. Environmental and economic criteria

VSM was originally created for the improvement of economic performance, but several studies have attempted to integrate sustainable development indicators into its implementation (Faulkner and Badurdeen, 2014). In Vinodh et al. (2015), a framework is proposed for a Sustainable VSM (Sus-VSM), in which green metrics are included in order to improve economic, environmental and social performance. The authors study the case of an automotive parts production plant, and collect both physical data (material and power consumption) and operational information (lead time, cycle time). Information on each activity is also collected, such as processing times or in-process inventories. A state map of the production line is made, including the gathered data related to the environmental and social metrics, and lean improvement measures are proposed according to different scenarios. While less extensive than MFCA regarding flow assessment and less precise than ITO in terms of activity description and linking, this approach has the benefit of grouping in a same representation environmental, economic and social metrics as well as operational parameters. In Brown et al. (2014), the Sus-VSM method is applied to different manufacturing environment (low variety - high volumes, high variety - low volumes and low variety - medium volumes respectively), showing its flexibility in regards to the shop floor configuration.

Lambrecht and Schmidt (2010) use Material Flow Networks (MFN) based on Petri nets to improve the efficiency of a waste incineration plant. They provide a prototype add-on to the LCA software Umberto in which production parameters are embedded in transitions and places (i.e. transformation and storage processes).

This allows for simulations of the production process with variable input parameters. Using successive simulations, their aim is to optimize the material flows for better efficiency. Although their add-on does lead to improvements in efficiency through better product mix, the authors also comment on its black-box nature which results in no analytic information about the material flow model, hiding potential improvements. A methodology for the mathematical modeling of MFNs is proposed in Lambrecht and Thißen (2015), and implemented in the case of a tungsten recycling facility in Lambrecht et al. (2018).

2.3. Multi-level approaches

The previously described methods focus on specific decision levels. We now review the methodologies that integrate both operational and strategic/tactical aspects in their implementation. This includes the information used, the modeling level or the decision support provided.

Despeisse et al. (2013) present an approach for the systematic identification of improvement opportunities in resource efficiency. They propose an Integrated Factory Modeling tool (Integrated FM), which spans different decision levels such as plant and process planning, supporting facilities or production scheduling. A production plant of a company is modeled using the IES Virtual Environment modeling and simulation tool (IESVE, 2019), and an analysis is made to identify improvement measures. Their simulation is extensive but requires a lot of data (physical, architectural, operational) in order to be carried out. The scale of the study (factory level, including supporting facilities and buildings) might not be suited to the modeling of a scheduling problem as it expands beyond the scope of the operational level.

Smith and Ball (2012) introduce a methodology for sustainable manufacturing through Material, Energy and Waste (MEW) flows. Based on the IDEF0 modeling methodology (Colquhoun et al., 1993), they propose a MEW Process Flows Modeling (MEW-PFM) representing the activities of a system as well as their input, control, output and mechanism. A hierarchical decomposition of activities can provide more detailed representations. A quantitative analysis is made on process flows, and a Pareto analysis ranks them based not only on their quantity, but also on the ability to influence them. A sequence of 16 guidelines is provided for the implementation of the methodology. The authors comment on the lack of dedicated metrics and tools for the modeling and evaluation of shop floor performance. This study brings insight on data collection and system modeling, but does not consider scheduling in its improvement methodology.

Finally, Kurdve et al. (2015) propose a Waste Flow Mapping (WFM) approach in a multi-site case study, examining wasted material flows, costs, material efficiency and operational efficiency in waste management systems of 16 automotive production sites. The identified waste flows are grouped into streams with similar characteristics, facilitating the implementation of improvement measures. Three steps are considered, namely a first mapping of value and non-value adding outputs, followed by horizontal and vertical efficiency analyses. Improvements in waste handling, management and treatment are then proposed based on the waste hierarchy advocated in Kurdve and Bellgran (2011).

2.4. Literature review analysis

All previously described methodologies can be grouped according to their decision level and criteria considered. As shown in Figure 2, only five out of seventeen

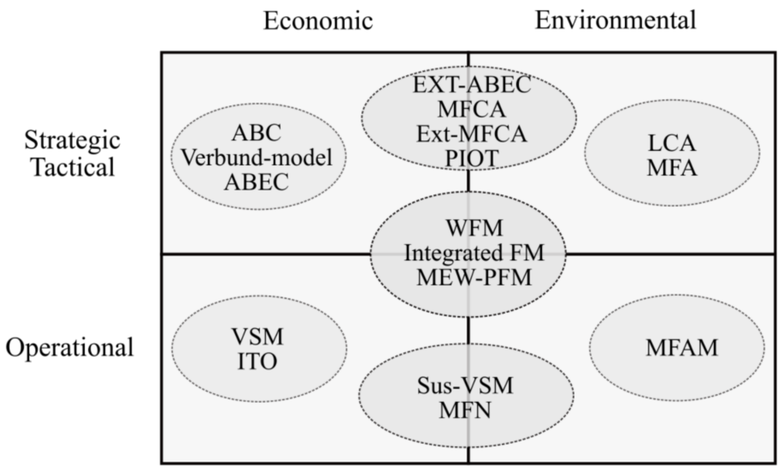

Figure 2: Methodologies grouping according to their included criteria and decision-level

methodologies consider both economic and environmental criteria on the operational decision level. While those five studies do consider operational parameters in their approach, scheduling is not explicitly considered as an improvement lever. Only Despeisse et al. (2013) include production schedules in their model (Integrated FM), and only Gould et al. (2016) use production scheduling to improve the environmental performance through the use of a GA (MFAM), although economic performance is not considered in the results. Finally, the decision-support tools provided take different forms: some enable the decision-maker to identify inefficiencies, and others directly provide improvement scenarios.

Several conclusions can be drawn from this literature review. First, an investigation of the existing flow assessment methodologies highlights the absence of dedicated tools relating flow assessment and waste-minimizing scheduling. Second, although none of the reviewed methodologies are directly fit to answer our research question, they provide insights regarding the problem at hand which can be used to build our required framework. LCA already has established and well-tried guidelines for defining the perimeter of a study and in allocation methods for environmental impact assessment. MFCA comes with a lot of documentation and examples of material flow inventory applications, both on environmental and economic aspects. From the operational point of view, the ITO method is effective in describing process parameters, and the MFN method provides examples of mathematical modeling of the flows. Finally, MFAM shows that it is possible to identify inefficiencies in a system using flow assessment and propose solutions through scheduling, even if this approach does not expressly consider scheduling parameters or economic evaluation in the flow assessment model. Although flow assessment is a promising tool in order to promote waste-minimization through scheduling, no dedicated methodology for this specific purpose has been proposed yet. This would allow for the unification of heterogeneous field of research with no definite terminology and a variety of problem types (Le Hesran et al., 2019a). In the following section, a new approach for the identification of waste-minimizing scheduling problems is presented.

3. Proposed methodology

This methodology provides comprehensive guidelines to identify waste and scheduling related problems within a system, facilitating the modeling of scheduling problems integrating waste minimization.

3.1. Goals and assumptions

The literature review shows that the existing flow assessment methodologies are not suited to answer our research question, i.e. to support the identification and characterization of waste-minimizing shop-floor scheduling problems. Indeed, they either provide only partial answers considering only one of the environmental and economic aspects, or do not focus adequately on the scheduling dimension. Using the insight provided by all these studies, we propose a methodology composed of four steps. The originality of this article does not lie in the novelty of the methodological steps proposed, as they are inspired from other preexisting approaches. Rather, its added value consists in utilizing and combining knowledge from the aforementioned studies in order to tackle a problem not yet covered by researchers. It is necessary to keep the level of complexity low enough for an easy use in an industrial context while still being representative of real-life situations. Several assumptions are made to facilitate the implementation of this methodology. Firstly, the data used is deterministic, with no uncertainty in parameters or unexpected machine failures. Secondly, the definition of waste for the rest of this study is the one used in the European environmental code (European Parliament and Council, 2008). This means that emissions such as gases, noise or light, whether they originate from energy consumption or from a process, are not considered. Also, no consideration is given to energy flows in this methodology, although this could certainly be a future extension given the numerous studies on energy flow assessment (Liu et al., 2018) and energy efficient scheduling (Giret et al., 2015).

Figure 3 summarizes the four steps that we propose for supporting the identification and modeling of waste-minimizing shop-floor scheduling problems. These steps consist in a first broad definition of the product system and its boundaries. It is then split into subsystems, the impacts of which are estimated (Step 1). A flow inventory (Step 2) and flow assessment (Step 3) are carried out on the subsystem(s) with the most potential for improvement. Finally, based on the information from the previous steps, a description of the waste minimizing scheduling problem is made

(Step 4). These steps are explained in detail in the following sections.

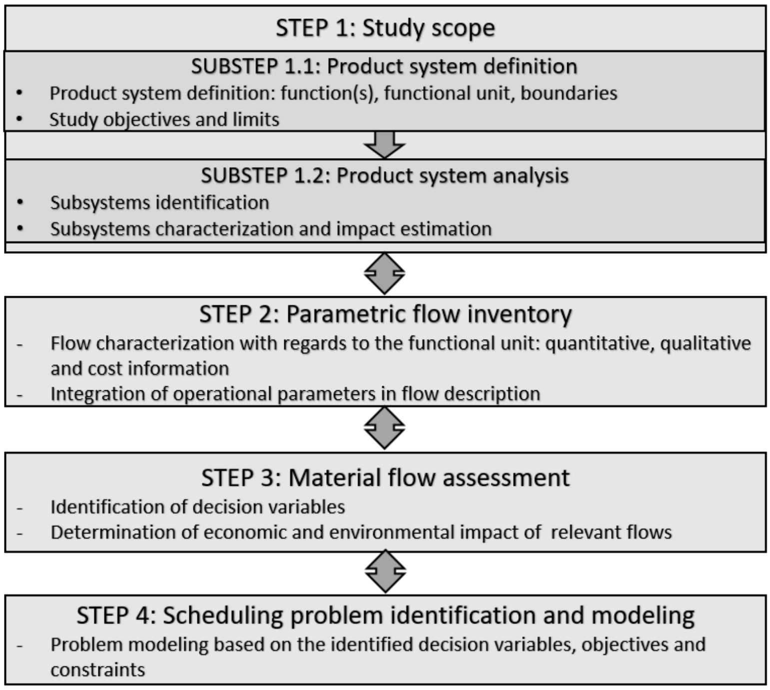

Figure 3: Proposed methodology implementation steps

3.2. Step 1: Study scope

This methodology answers a need by companies to conform to environmental regulations, to obtain a certification, to comply with larger corporate policy or to improve brand image, without investing in new equipment. The choice of the product system considered can be influenced by this motivation. For example, a legal injunction to reduce a specific pollutant will make the product system responsible for generating this pollutant the focus of this methodology. The aim of this first step is to identify processes or activities within a product system where improvements could be made regarding waste generation.

3.2.1. Substep 1.1: Product system definition

This first substep defines the scope of the system considered. Following the guidelines of the ISO 14040 (2006) for LCA, several items should be clearly identified and defined, which are summarized in Figure 4.

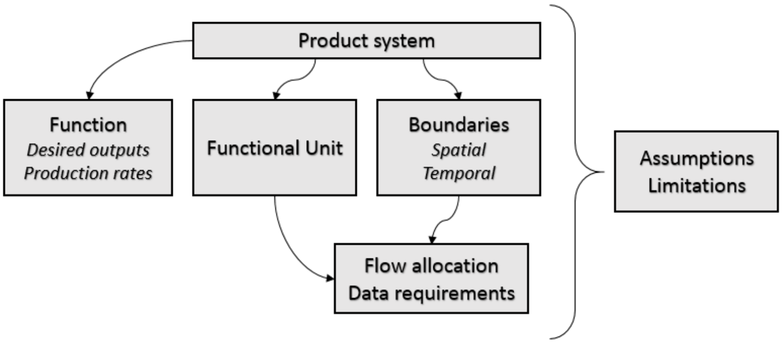

Figure 4: Scope and boundaries definition

The product system is "a collection of unit processes with elementary and product flows, performing one or more defined functions, and which models the life cycle of a product" (ISO 14040, 2006). It can be a whole factory or a subpart of a system. Each of these unit processes perform one or several functions, which all contribute to the function of the product system as a whole. This function should be defined in terms of objectives, such as the manufacturing of certain products, and specify if any other characteristics are required for the production. Such characteristics can be e.g. a minimum production rate or a certain product quality range.

Once the product system and its function have been defined, its boundaries can be determined. The spatial boundary includes all unit processes that fulfill a part of the system function as well as auxiliary processes (i.e. processes that contribute to the overall objectives without directly being involved in the product manufacturing) such as wastewater treatment plants or byproduct regeneration units. The input and output flows that enter or exit the system boundary are called elementary flows, and will be the basis of the impact assessment. This assessment relies on determining the physical quantities of materials which circulate in the system. These physical quantities are later translated into environmental (based on a number of environmental indicators) and economic (i.e. the cost of generating and managing each waste output flow) impacts using LCA and a cost assessment method. It is necessary to determine a temporal boundary for the system, which defines the length of time over which the flow assessment is carried out.

The Functional Unit (FU) is also a concept from the LCA methodology, and represents the "quantified performance of a product system for use as a reference unit" (ISO 14040, 2006). The functional unit may be a certain quantity of product(s) to manufacture, a set amount of production time or a certain input flow for example. Flows within the system are defined to fulfill the function expressed by the functional unit.

The flow allocation corresponds to the repartition of input and output flows between all processes for the determination of their respective impacts. Procedures for flow allocation can be found in Pradel et al. (2016). Finally, it is necessary to define the requirements regarding data collection (timescale, accuracy...) and explain the assumptions made regarding the product system as well as the limitations of the study. An example of product system is shown in Figure 5.

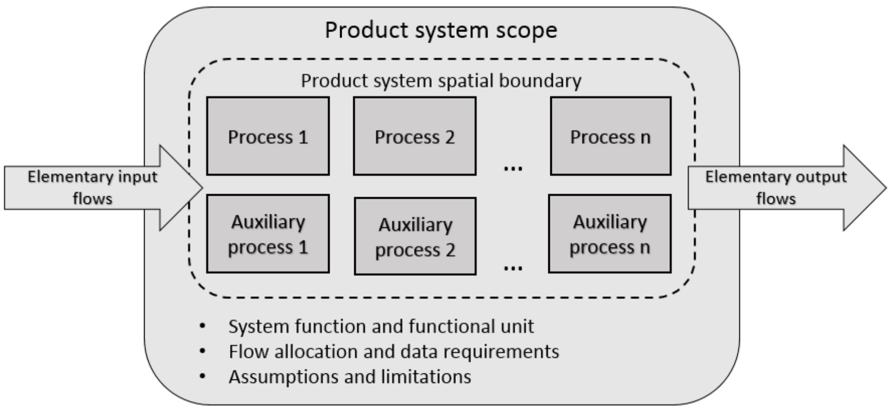

Figure 5: Example of product system

The product system definition is important as the impacts will be calculated based on the elementary output flows. The results and improvement measures proposed might change by including or not some unit processes and auxiliary processes. Product system definition is not a one time process, and should be modified or updated as the methodology implementation progresses and new information is available. It is also relevant to consult the decision-makers involved with the product system, as they can bring information on the operating process, waste management or production objectives.

3.2.2. Substep 1.2: Product system analysis

Once the product system and study scope are described, it is necessary to identify the most relevant parts to focus on. The first step is to accurately delimit all the independent subsystems (subset of quantity centers) composing the global product system. Two subsystems are independent if no constraint or restrictions are carried from one to the other (either through material or information flows), meaning that their respective scheduling problems are decorrelated. Such decoupling can appear e.g. through the use of buffers between processes, and should be identified by looking at the products structure trees. Checking for buffers and bottlenecks can also provide information. Subsequently, the different quantity centers composing each subsystem need to be characterized. According to the ISO 14051 (2011) standard on MFCA, a quantity center is a selected part or parts of a process for which inputs and outputs are quantified in physical and monetary units. Quantity centers can represent transformation (i.e. processes where the nature of flows can be affected), transport or storage processes, such as presented in Gould and Colwill

(2015). Information regarding quantity centers should be gathered using the ITO method (Schubert et al., 2011), as it provides information regarding both the flows that cross a quantity center (input and output) and the parameters within that quantity center affecting these flows. Basic information to be collected (see Figure 6) includes:

- Input flows and their characteristics (type, concentrations, composition, cost...)
- Process parameters: description of how these processes affect the input flows and operational parameters (i.e. throughput, setups, capacity, operating costs, failure rate, resource consumption and efficiency...).
- Output flows characteristics based on the input flows and process parameters.

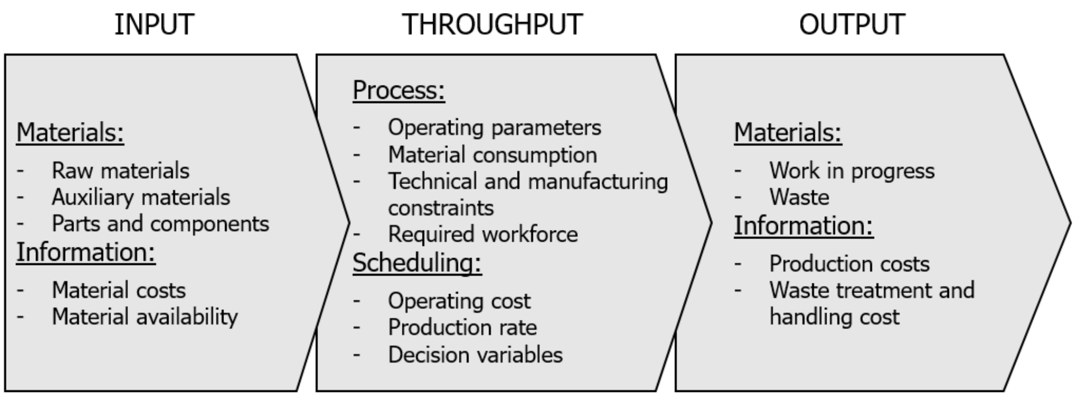

Figure 6: Example of quantity center characteristics

The ISO 14033 (2012) standard provides information regarding environmental data collection and usage, especially regarding data aggregation for the subsystems and product system.

Regarding information on operational parameters, already available data should be collected using technical documents of machines and processes or knowledge from experts and machine operators. If more data is necessary, the addition of adequate sensors or measurements might be required. Regarding the evaluation of costs, the Ext-ABEC method proposed in Cagno et al. (2012) calculates the costs of products, by-products and waste. The resources and activity costs are taken into account, and a set of cost indexes is given to evaluate the efficiency of production.

Information flows circulating in the subsystem should be detailed. As for the VSM representation (Vinodh et al., 2015), such flows include data regarding time-related information (due dates, schedule updates...), orders or stock levels. It is also important to consider the interactions between all quantity centers within a shop floor. It is necessary to determine how quantity centers are related to each other and which flows they exchange. Information such as the objectives or scheduling constraints can be linked to several quantity centers simultaneously, or even to the subsystem as a whole. Using the knowledge of people responsible for production planning, operators and foremen is a powerful way to gather the necessary information.

At this point, all the different subsystems are identified and characterized. The inputs, outputs and throughput of each quantity center are known, and the relationships between them understood. This results in a triple representation for each subsystem, namely the physical, economic and environmental one, as shown in Figure 7. Operational and cost information appears in each quantity centers (rectangles), and the flows (arrows) circulating in the system carry physical and economic information as well as environmental information for waste flows, as is proposed in Schmidt and Nakajima (2013).

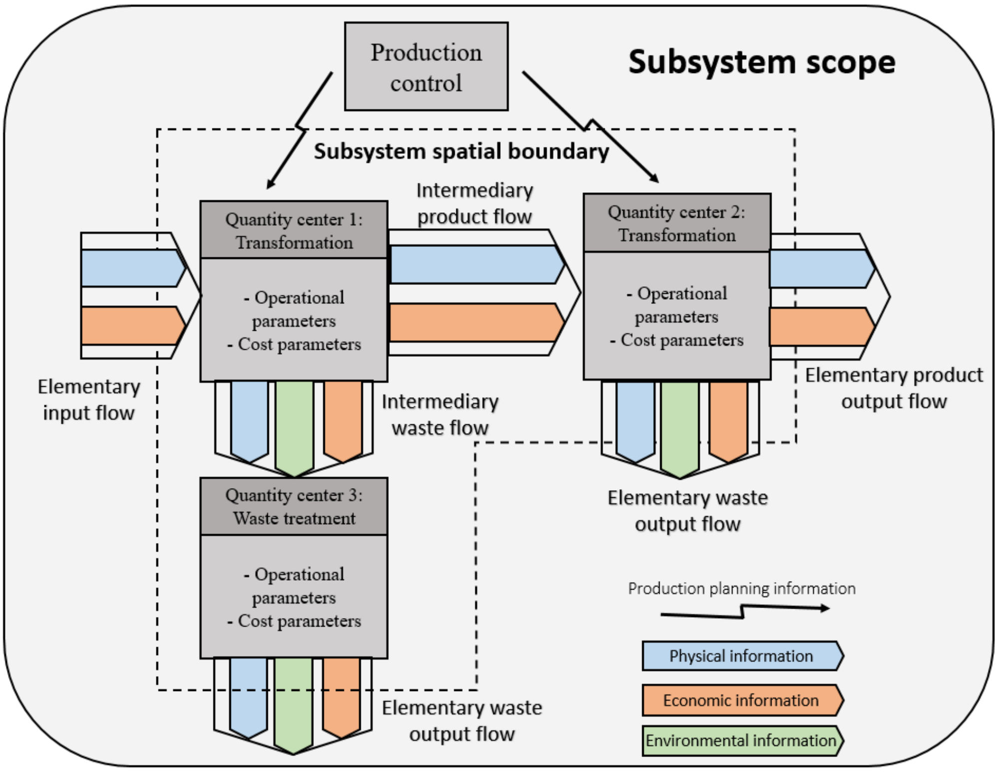

Figure 7: Example of subsystem with three quantity centers - physical, economic and environmental representation

Based on the gathered information regarding the different subsystems, it becomes possible to estimate their respective impacts (economic and environmental). This can be done by looking at the aggregated waste generation of each subsystem as well as the costs entailed by these generated waste. The ISO 14031 (2009) standard on Environmental Performance Evaluation provides comprehensive guidelines on how to interpret the impact of waste flows. Information regarding waste quantities and cost is available through the accounting and Quality, Health, Safety and Environment (QHSE) departments. The nature of materials used and their respective monetary value and/or environmental impact need to be taken into account. As an example, a small amount of high value/high impact waste might have more importance than a bigger flow with more benign characteristics. Also, current and future legislation need to be considered, as well as normative aspects. If a company intends to apply for a certification (e.g. the ISO 14001 standard), more emphasis might be needed on certain types of waste. Decision-makers which are involved with the product system should also be consulted.

What these indicators represent also needs to be explained so that the decision-makers can make an informed choice based on their priorities. It is important to remind them of the regulations that can apply, as well as explain how each indicator impacts the current or future objectives of the system.

Table 1: Economic and environmental indicators

Environmental indicators	Economic indicators
Material intensity	Materials cost
LCA Environmental impact	Systemic cost
	Management cost

The environmental indicators chosen, shown in Table 1, are the quantity of waste generated per FU (material intensity) and the environmental impact represented by their resource usage and end-of-life treatment. The environmental impact is calculated using an LCA software, and can include as many impact categories as necessary. Since not all indicators might be relevant, a screening can be carried out for indicators with negligible impacts to reduce unnecessary information. The ReCiPe assessment method (NIPHEN, 2019) provides three aggregated endpoint indicators representing damage to human health, ecosystem and resource availability respectively, which can be an effective way to present environmental impacts in a concise and comprehensive manner. It is also important to indicate when assumptions are made regarding the LCA, since databases might not always contain the exact data regarding some materials, wastes or processes.

Regarding the economic assessment, a cost division commonly used in EMA and other environmental cost accounting methods consists in materials costs, systemic costs and waste management costs (Jasch, 2008). We use the same classification as it accurately depicts the costs involved with waste and can easily be aggregated to represent the full cost of a waste flow.

The evaluation of subsystems depends on the priorities of the decision maker (e.g. environmental policy or ecosphere). It is necessary to confer with them to decide on the rank assigned to each subsystem, following these steps:

1. Select a subsystem;
2. Using the information collected in steps 1.1 and 1.2, calculate the environmental and economic impact indicators listed in table 1;
3. Through discussion with the decision-makers, define importance of the environmental and economic criteria and rank subsystems;
4. Look at the regulations and environmental objectives set by the company and reassign ranks if necessary;

Once the subsystems have been ranked, they are then further studied to check if scheduling is a possible lever to reduce the impacts of waste production. If possible, the magnitude of the possible improvement should be estimated, as some subsystems with lesser impacts but higher flexibility might be more relevant to improve than higher ranked but very constrained ones. If a subsystem does not have any scheduling lever available, it is removed from the ranking and the next one is checked. Once all subsystems have been checked this process ends and the second methodology step can start.

Since many mechanisms related to scheduling can be responsible for waste generation, looking at existing studies regarding waste-minimizing scheduling might provide insight regarding which parameters are important. Le Hesran et al. (2019a) propose a literature review on waste-minimizing scheduling, as well as a classification of scheduling concerns related to waste generation which can provide a first basis for identifying important parameters. The application of the ITO method should also provide sufficient information to ensure that all sources of waste are known. Each waste output from a quantity center should be quantified as a function of its operating parameters (e.g. as a scrap percentage, proportional to a number of setups). Storage and transportation processes, while less likely to generate waste, should also be considered from such an angle. Such considerations include, but are not limited to, product expiration due to long storage times; product deterioration during transportation; or leaks from storage units. Subsystems with no identified scheduling lever are removed from the ranking, although the obtained information remains useful to consider other waste prevention methods (e.g. process or materials change, reuse, ecodesign ...).

After this iterative process, only the most relevant subsystems selected are kept in the product system. This allows for a synthetic representation and description, and avoids time-consuming investigations on systems that cannot be improved through scheduling.

3.3. Step 2: Parametric flow inventory

After having described the different quantity centers composing the product system, the material flow inventory step aims at mapping and quantifying the circulation of flows within the system. According to the ISO 14051 (2011) on MFCA, three main types of flows are identified:

Initial input flows: the flows that enter the boundaries of our system. Those can be raw materials for the production, subcomponents, or auxiliary materials (materials used in a process but not directly used for the product, such as cleaning water). The characteristics of these flows need to be precisely defined (quantity, composition, volume...) as they will be used to calculate all downhill flows.

Intermediate flows: the flows that circulate within the system boundaries, from one quantity center to another. Their properties can change depending on the quantity center they go through (i.e. wether it is a transformation process or not). They can be split or combined.

Final output flows: the flows that come out of the system boundaries. Those flows are the ones that serve to calculate the different impacts of the system in terms of cost or environmental impacts, and are the results of all the transformation processes present in the system.

Based on guidelines provided by the ISO 14051 (2011), the different types of flows within the system should be categorized as they will have different effects on its evaluation. Raw materials, finished and semi finished products, by-products and waste might not need the same indicators. As an example, it is more important to gather environmental information on waste flows than on finished product (since they are the only ones considered in the LCA), and by-products that are reused within the system might not need to be considered. Also, creating families of similar products or materials (depending on shape or color for example) can simplify the model, as long as those differences do not have an impact on the schedule or waste generated (all products in a family need to have the same final impacts). This allows for a reduced number of flows to account for.

It is also necessary to integrate the operational information gathered during step 1.2 as flow characteristics are affected by these parameters. Once all the data regarding the different flows and quantity centers has been gathered, the overall system can be modeled. The initial input flows enter the system boundary, and go through a first set of quantity centers, where they can be transformed, stored or transported. After calculating the internal flows resulting from these centers, those go into the next set of quantity centers, and so on until they exit the system boundaries as final output flows. At each step, these flow properties are defined based on the operational parameters of each center. The final output flows are ultimately expressed according to the parameters of all the quantity centers they went through, or "parametric assessment". This process is represented in Figure 8 for a product system with three quantity centers and two initial input flows.

3.4. Step 3: Material flow assessment

Step 3 is the material flow assessment, where the waste output flows are characterized. Their environmental and economic impact evaluation is carried out, and their parametric representation is studied to identify how each parameter affects the output waste flows. This serves the dual purpose of finding which flow or process is responsible for waste generation/cost and in which measure, as well as identifying all parameters (e.g. number of setups, operating speed…) that can influence both

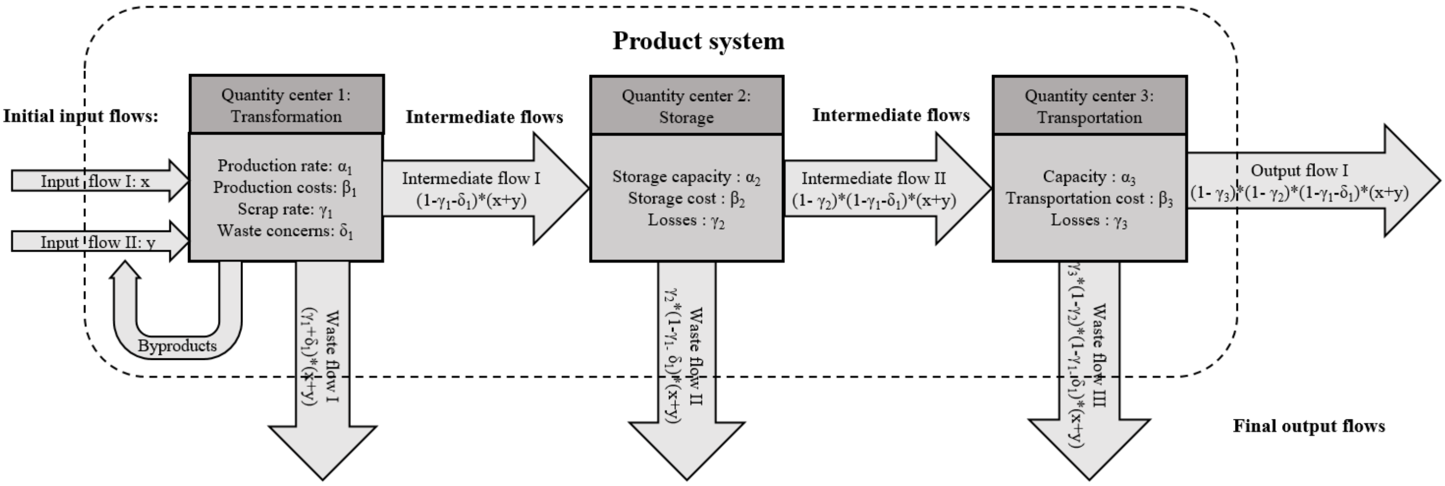

Figure 8: Example of parametric flow inventory with three quantity centers and two input flows

scheduling and the quantity of waste. An LCA evaluation can be carried out for precise environmental impact determination, and the ext-ABEC method provides waste-related costs. It is also important to consider scheduling-related costs such as inventory and include them in the economic evaluation. This provides the objective function that will be used later for problem modeling. As an example, the impact assessment of the product system presented in figure 8 is done below (all parameters are given in the figure).

Three waste flows are identified, one for each quantity center, due to scrapped products and process waste, storage losses and transportation losses respectively. The LCA should be carried out on these three flows which can be summed as :

$$\text{Waste}_{total} = (x+y) \times ((\gamma_1 + \delta_1) + \gamma_2 \times (1 - \gamma_1 - \delta_1) + \gamma_3 \times (1 - \gamma_2) \times (1 - \gamma_1 - \delta_1)) \quad (1)$$

This provides an accurate assessment of the contribution of each flow to the total impact. Additional assessments can be made using different values for the waste related parameters, which can allow for an estimation of the new impacts if improvements were made. Similarly to what is proposed in Section 3.2.2, use of the ReCiPe assessment method and its three aggregated endpoint indicators is recommended. More precise midpoints indicators can be used if relevant.

As explained in Section 3.2.2, three types of costs are to be considered regarding waste, namely material, systemic and management costs. To that must be added the costs related to scheduling such as inventory costs in the case of the second quantity center. Material costs consist in the price of materials composing all three waste flows, whose quantities are given by the three waste output equations. Systemic costs consist in the production costs β_1 for quantity center 1, handling and storage space costs β_2 in quantity center 2 and transportation costs β_3 in quantity center 3. Management costs correspond to the storage, disposal and treatment costs of all three waste output flows. Finally, holding costs resulting from inventory keeping in quantity center 2 need to be added. Same as for the environmental impact assessment, some parameters can be modified to look for potential savings.

3.5. Step 4: Scheduling problem identification

The aim of this step is to summarize all the information (operational, environmental and economic) gathered during the previous steps in order to identify the scheduling problem and help modeling it. The main characteristics of a scheduling problem are (Pinedo, 2008):

Problem data: what is known about the system and schedule (e.g. processing times, lot sizes, due dates…).

Decision variables: variables that can be adjusted in order to improve the objective function (e.g. operations starting times, operations order, operating parameters…)

Workshop configuration α: how the different quantity centers are related, and how this affects the possible scheduling process (e.g. number and types of machines, types of operations).

Constraints of the problem β: what is allowed and what is not when designing a schedule (e.g. due dates, precedence constraints…).

Objective function γ: what we seek to improve when using the scheduling model. It depends on the decision-maker and constraints of the system, and includes both an economic and environmental component.

Table 2 sums up all the information related to the problem and at which step this information can be obtained.

Table 2: Problem identification process

Information	Identification step	Resulting notation
Problem data	Step 1 and 2	
Decision variables	Step 1.2, 2 and 3	Decision variables
Workshop configuration	Step 1 and 2	α
Constraints	Step 1 and 2	β
Objective functions	Step 3	γ

The data sets are determined using the information from step 1 and 2. Decision variables are the production parameters that influence both scheduling and waste generation. They are first identified during substep 1.2, and then quantified during steps 2 and 3. The α and β fields (workshop configuration and scheduling constraints) can be determined based on the information gathered during steps 1 and 2. Finally, the γ field (objective function) is identified during step 3 by considering all waste outputs and costs that can be influenced by the decision variables. This can serve as a basis for representing the problem mathematically by translating the objective functions and constraints into mathematical equations using the defined data. This can be done using Mixed Integer Linear Programming (MILP).

4. Application example

In this section, a practical application of the proposed methodology is carried out. This case involves a hubcap production plant which includes raw plastic reception and oven drying, injection moulding, painting, quality control and expedition. The different steps of the methodology are successively applied in order to identify the links between scheduling and inefficiencies in resource usage and waste generation, as well as define the scheduling problem. Through this example, the applicability and results of this methodology are demonstrated. A first study of this case has been presented in Le Hesran et al. (2019b).

4.1. Application example: Study scope (Step 1)

The production of the hubcap manufacturing plant ranges from raw materials reception and preparation to the expedition of finished products. In Substep 1.1, the product system consists in the whole production site, including all storage facilities for materials, products and waste. The production is composed of three main families of products: plastic pieces, unicolor hubcaps and bicolor hubcaps. Hubcaps are composed of PVC onto which one or two paint coatings can be applied. After moulding, a metallic ring is inserted while a brand logo is clipped during the final quality control. Stringent requirements placed on automotive parts suppliers place each lot of hubcaps under a hard due date constraint. The functional unit chosen is the production of one day's worth of hubcaps, as the production schedule is determined on a daily basis. Such a functional unit combines scheduling (through the daily planning of production) and waste generation (represented by the daily waste output in normal operating conditions). The daily production capacity is 25 000 hubcaps, with job sizes ranging from 800 to 2000 pieces, hence between 10 and 30 jobs per day. An average of 250 workdays per year is assumed in this study. The spatial boundary considered for this product system is represented in Figure 9. Since due dates are involved, the temporal boundary for production is set as the last due date of the lots to be produced.

Substep 1.2 focuses on each independent subsystem to estimate their cost and environmental impact, as well as the potential to mitigate these impacts using scheduling. As can be seen from the product system description in Figure 9, the plant is divided into three main workshops, namely the preparation, moulding, and painting/finishing ones. Buffer storage is present between each workshop, meaning that they can be considered as independent subsystems, as long as the buffer size and production capacity of each workshop are assumed to be sufficient.

The preparation workshop is responsible for producing the plastic used by the moulding machines. It generates few waste, namely packaging and wastewater. It has no constraints related to scheduling.

The moulding workshop manufactures plastic pieces, painting masks and raw hubcaps, and includes injection moulding machines, an assembly post as well as a quality control post. Its generated wastes are residual plastic coming from the moulding process and scrapped products from the quality control. From a scheduling perspective, waste production is impacted by changes in plastic compositions for the

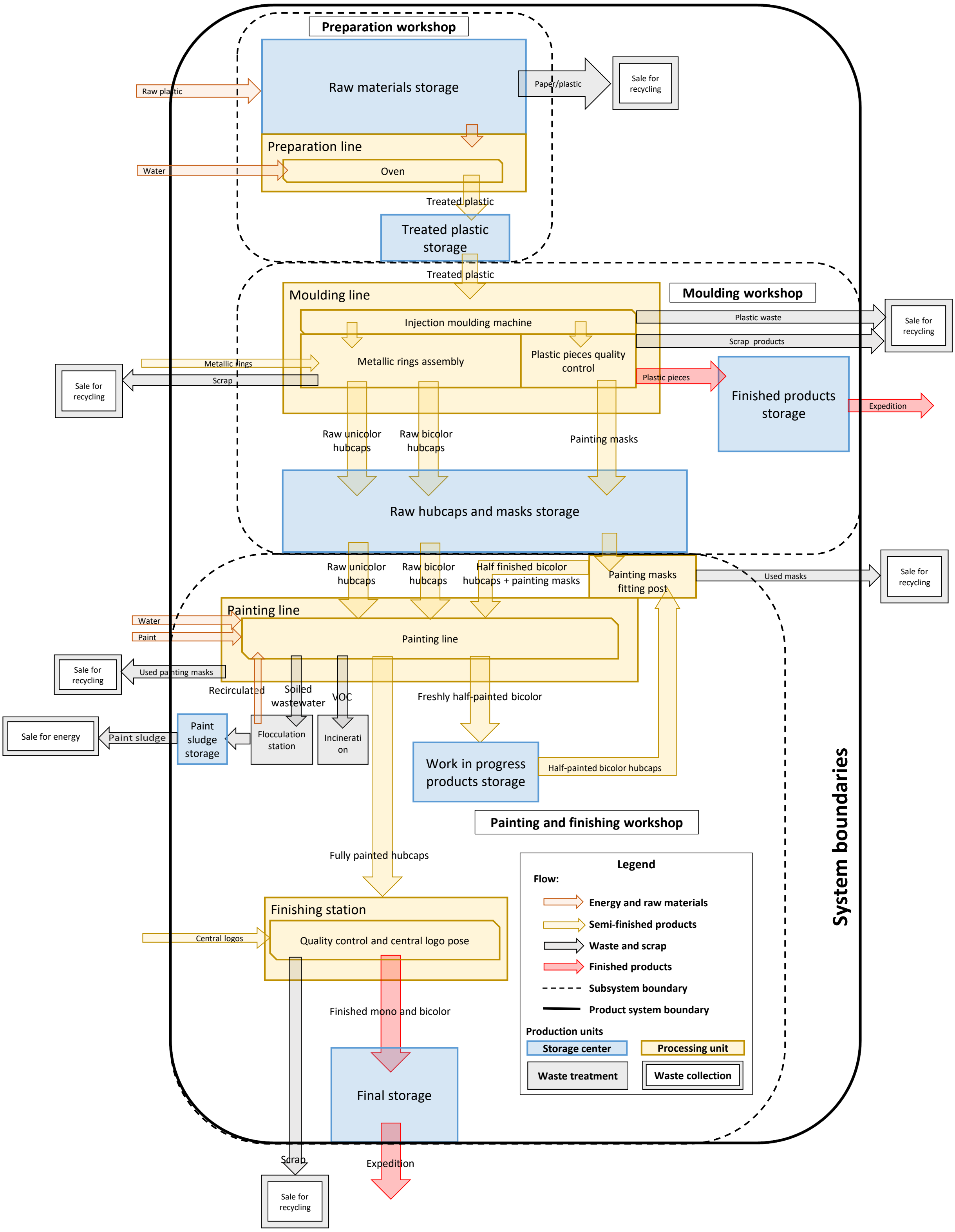

Figure 9: Hubcap product system description

different pieces as well as mold changes, as the machines need to be purged each time a setup is required.

Once produced, the raw hubcaps and painting masks are sent to the painting and finishing workshop where they go through a painting line. Unicolor hubcaps only need a single coating, and go through the painting line only once before being sent to the finishing station. Bicolor hubcaps need to receive two coatings, with a mandatory 48h drying period between each coating in an intermediary storage. Painting masks are used during the second passage in the painting line and can be reused up to five times. All painted hubcaps are sent to the finishing line where a central logo is inserted and quality is controled. This workshop generates different types of wastes, namely paint sludge, scrapped products and used painting masks. Paint sludge is the result of soiled wastewater from the painting line going through an on-site flocculation process. It is considered a dangerous waste by the French environmental code (waste type 080113*, Assemblée des Chambres Françaises de Commerce et d'Industrie (2018)) and needs to be stored in a separate building before collection for energy recovery. Paint sludge comes from two separate mechanisms: the normal functioning of the painting line, and the setup operations required when changing color. Like in the moulding workshop, scheduling impacts the waste generation through the number of required setups, i.e. color changes. The moulding and the painting/finishing subsystems have been identified as opportunities for reducing waste through scheduling. To gather information on these subsystems and waste management, an interview was conducted with a QHSE manager. Missing information was extrapolated using studies from similar fields or from public sources.

The yearly quantity of non-hazardous waste collected (not including scrapped products) is estimated to 54 tons. Non-hazardous waste is stored in outdoors metallic containers which were purchased by the company and have already been amortized. The price for plastic waste collection and recycling was estimated at 180€ per ton, based on price estimations by the French environmental agency (ADEME, 2019). The price for one ton of PVC is estimated at 912€, based on recent French market prices (UCAPLAST, 2019), while the price for one ton of ready-to-use paint is estimated to 3000€. Operating prices were calculated based on the workforce of each workshop (The Boyd Company Inc, 2016).

In the painting and finishing workshop, the company reported an average of 120 tons of paint sludge per year, with an annual cost of 38 000€ for collection. This price includes neither the operation and maintenance cost of the flocculation plant nor the handling cost for packaging and transport into storage. Salihoglu and Salihoglu (2016) report that costs for the flocculation station management represent around 46% of paint sludge management, which is the figure used for this study. A specific hangar is used for the paint sludge storage, further adding to the overall cost. Water is recirculated after treatment. Regarding environmental regulations, emission levels of paint sludge are currently compliant. There is however a concern regarding the ISO 14001 certificate renewal.

Table 3 gives the environmental and economic indicators assessment regarding the plastic and paint sludge waste flows. Treatment costs of paint sludge include management cost (152€ per FU), the flocculation station operating cost (70€ per FU) and waste storage cost (20€ per FU). Environmental impacts were calculated using the OpenLCA 1.7.4 software and the Ecoinvent 3.1 database, and consider both resource consumption for plastic and paint production as well as end-of-life treatment for wastes. LCA method used is the ReCiPe with three aggregated indicators (damage to ecosystems, damage to human health and damage to resources availability) for better clarity. In the real-life situation for this case-study, paint-sludge is sent to a cement-kiln for co-incineration. This type of end-of-life treatment being unavailable in the Ecoinvent database, the end-of-life treatment method used for calculating the paint sludge impact was the hazardous waste incineration process. It is still representative of a typical paint-sludge treatment process, which is classified as a hazardous waste by the European waste code (European Commission, 2000). Scrap plastic is sold on the global market before being grounded into pellets for reuse. As shown in Table 3, paint sludge has a larger environmental impact as well as a higher economic cost. It is subject to governmental regulations, and a cause of concern regarding the ISO 14001 certification. For all these reasons, it was decided to limit this study to the painting and finishing workshop only.

Table 3: Moulding and painting workshop wasteflows assessment

	Impact	**Moulding workshop** Scrap Plastic	**Painting Workshop** Paint Sludge
Environmental	Material intensity	216 kg per FU	480 kg per FU
	Ecosystems (PDF $\times$ m^2 $\times$ year)	1.05×10^{-5} per FU	7.05×10^{-5} per FU
	Human health (DALY)	4.9×10^{-3} per FU	29.2×10^{-3} per FU
	Resources (MJ surplus)	57.5 per FU	104.5 per FU
Economic	Materials cost	197 euros per FU	1440 euros per FU
	Systemic cost	4901 euros per FU	3770 euros per FU
	Treatment cost	39 euros per FU	242 euros per FU

4.2. Application example: Parametric flow inventory (Step 2)

The quantity centers contained in the painting and finishing workshops are:

- Painting line
- Painting masks fitting post
- Semi-finished products storage
- Flocculation station
- Paint sludge storage
- Finishing station
- Final storage

The ITO method is applied to each quantity center to characterize it. The indices corresponding to each parameter are shown in Table 4, and the detailed painting and finishing subsystem flow inventory shown in Figure 10.

Table 4: Parameters and flow indices

Cost parameters		Operational parameters		Waste parameters		Flows	
m_c	Material cost	p_r	Production rate	s_r	Scrap rate	x	Initial input flow
o_c	Operating cost	cap	Capacity	c_r	Conversion ratio	y	Intermediary flow
s_c	Storage cost	s_t	Setup time	r_r	Recirculation ratio	z	Final output flow
wt_c	Waste treatment cost	nbs	Number of setups	set_w	Setup waste	QC	Quantity center
set_c	Setup cost			o_w	Operating waste		

Paint sludge
$$z_1 = c_{r_3} \times ((x_1 + x_2) \times o_{w_1} + nbs_1 \times s_{w_1}) \tag{2}$$

Wastewater
$$z_2 = (1 - r_{r_3}) \times (1 - c_{r_3}) \times ((x_1 + x_2) \times o_{w_1} + nbs_1 \times s_{w_1}) \tag{3}$$

Used masks
$$z_3 = x_2 \times (1 - s_{r_1}) \times o_{w_6} \tag{4}$$

Scrapped products
$$z_4 = x_1 \times s_{r_1} + x_2 \times s_{r_1}^2 \tag{5}$$
$$z_5 = x_1 \times (1 - s_{r_1}) \times s_{r_4} + x_2 \times (1 - s_{r_1})^2 \times s_{r_4} \tag{6}$$

Using the waste and operational parameters, each waste flow can be calculated based on the input flows as shown in equations (2)-(6). As an example, the paint sludge waste flow z_1 originates from the painting line operating waste multiplied by the

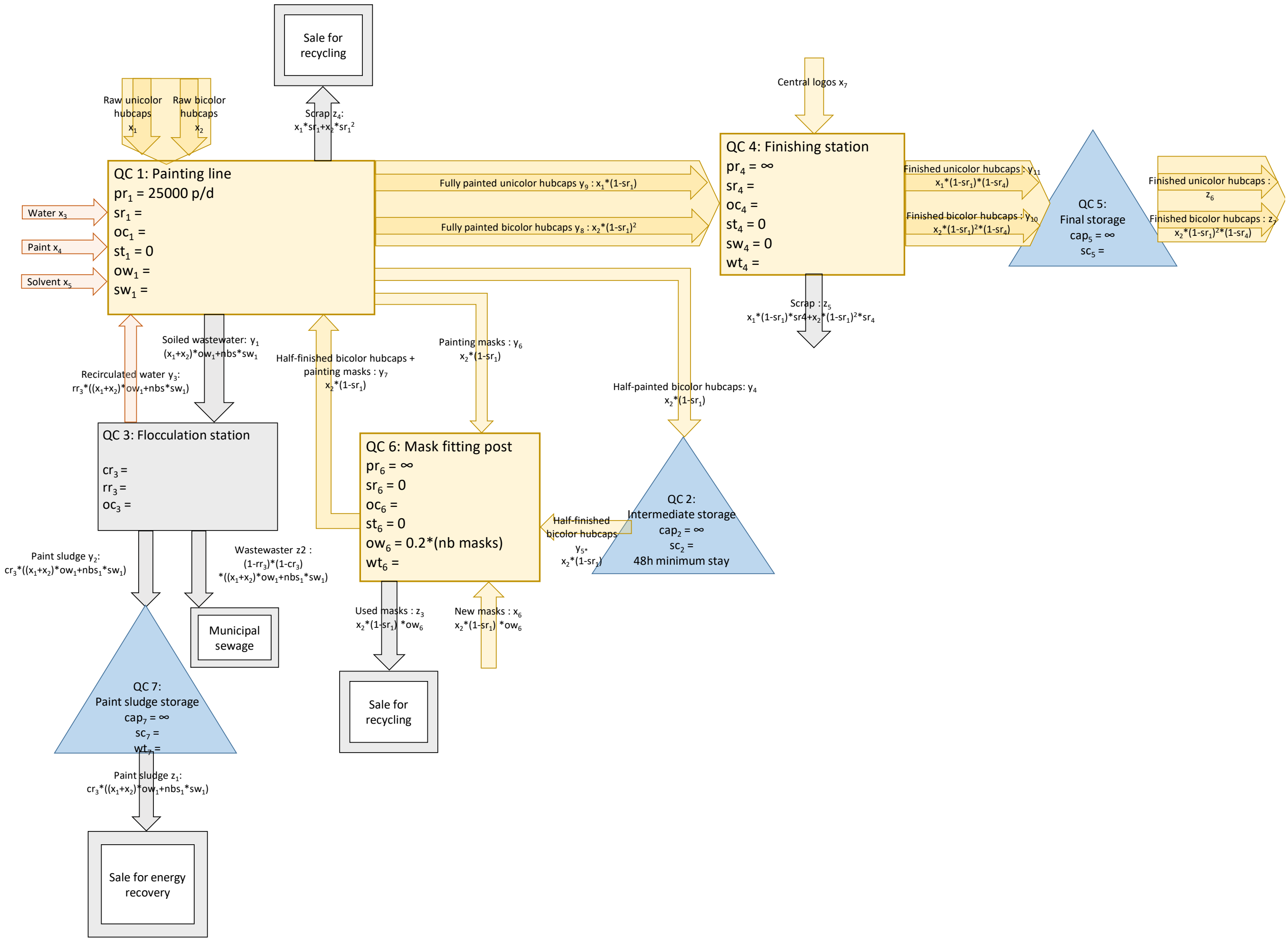

Figure 10: Painting and finishing subsystem flow inventory

product flows x_1 and x_2 plus the waste generated by setups, weighted by the conversion ratio c_{r3} of the flocculation station. The parametric representation allows for quantifying each flow circulating in the subsystem as an equation. Cost information is also represented, and will be used in the next flow assessment step.

4.3. Application example: Material flow assessment (Step 3)

As the flows have all been quantified, their respective impacts and costs can be determined. Focus is given to the elementary output flows of waste and products, as those are the main factors to determine the economic and environmental impacts of the subsystem.

It can be seen that only output flows z_1 and z_2, respectively paint sludge and wastewater, are affected by the number of setups of the painting line nbs_1. Since no other parameter can be affected by scheduling, output flows z_3, z_4 and z_5 are not considered in the rest of this analysis.

Let us recall equation (2):

$$z_1 = c_{r_3} \times ((x_1 + x_2) \times o_{w_1} + nbs_1 \times s_{w_1})$$

We know from Section 3.2.2 that z_1 is equal to 120 tons per year, or 480 kg per day with 250 working days a year. Parameter c_{r_3} is the ratio of soiled wastewater converted into solid paint sludge during the flocculation process. The value used here is taken from Talbert (2007) with c_{r_3}=0.6 kg of paint sludge per liter of soiled wastewater. The transfer efficiency, i.e. the percentage of painting mix (paint plus solvent) that actually ends up on the product, is chosen as 60 percent which is an average value for liquid paint spray techniques. Paint mix consumption is 80 liters per hour of operation for the painting line, meaning that $ow_1 = 0.4 \times 80 = 32$ liter per hour. With an average of 20 operating hours per day ($x_1 + x_2 = 20$), we can calculate the total daily solid waste generated by operating the painting line (not including setup waste):

$$z_1^{\text{operating}} = c_{r_3} \times ((x_1 + x_2) \times o_{w_1} = 0.6 \times 20 \times 32 = 384 \text{ kg per day}$$

A daily average of 384 kg of paint sludge is generated through the operation of the painting line, which is 96 tons a year. The remaining 24 yearly tons, or 96 kg per day, come from cleaning operations after each setup as defined below:

$$z_1^{\text{setup}} = c_{r_3} \times (nbs_1 \times s_{w_1}) = 96 \text{ kg per day}$$

From this last equation, we can see that reducing the number of setups nbs_1 by half through better scheduling would reduce z_1^{setup} by half. This would avoid 12 tons of paint sludge a year, thus a 10% decrease on the total paint sludge generation of the company.

For equation (3), all of the water is recirculated on-site after going through the flocculation station, with $r_{r_3} = 1$, meaning that no reduction is necessary.

While the number of setups does not appear in any other flow from the sub-system, it still affects the rest of production at the operational level in terms of lot-sizing. Indeed, when considering unicolor and bicolor hubcaps as two products (differences in hubcaps shape are not relevant in the painting line among a same family), the lot-size for a production order is determined by the number of hub-caps processed between each color change. Increasing the number of setups tends to reduce lot-size, and conversely. This in turns affects the inventory (both for the intermediate and final storage) cost, as it depends on the number of products stored at any moment. In this perspective, lot-size becomes the determining factor for balancing the number of setups (and by extension environmental costs) and the time spent in inventory (holding cost). The economic objective for this problem should include both the waste represented by flows z_1 and z_2, as well as the inventory costs. Also, because of the due dates constraint, a minimum number of setups might be unavoidable in order to comply with the orders requirements.

Based on the different activities and cost drivers described in the Ext-ABEC method, the detailed cost equations of flows z_1 and z_2 are given below:

$$c_{z_1} = m_{c_1} \times z_1 + c_{r_3} \times o_{c_3} \times y_1 + c_{r_3} \times nbs_1 \times set_{c_1} + s_{c_7} \times y_2 + wt_{c_7} \times y_2 \tag{7}$$

$$c_{z_2} = m_{c_2} \times z_2 + (1 - c_{r_3}) \times o_{c_3} \times y_1 + (1 - c_{r_3}) \times nbs_1 \times set_{c_1} \tag{8}$$

These costs are composed of different parts. In the case of z_1, the meaning of each term composing the equation is detailed below:

- $mc_1 \times z_1$: material cost of flow z_1, which is dependant on the price of flows x_3, x_4 and x_5;

- $c_{r_3} \times o_{c_3} \times y_1$: cost of operating the flocculation station. This operating cost is divided between flows z_1 (paint sludge) and z_2 (wastewater) according to the conversion ratio (part of the input flow transformed into paint sludge vs part transformed into water);

- $c_{r_3} \times nbs_1 \times set_{c_1}$: setup cost for the painting line. In this case, the assumption is made that the setup cost is wholly transferred to flow y_1 (soiled wastewater originating from the painting line) and not to the product flows y_7 and y_8. Similarly to the previous entry, this cost is divided between the paint sludge and wastewater using c_{r_3};

- $s_{c_7} \times y_2$: storage cost for the paint sludge. In this specific case, the storage cost is not dependant on time, as paint sludge does not possess any holding cost. It represents the cost of using and maintaining the building and containers used for storage;

- $wt_{c_7} \times y_2$: waste treatment cost, which is the price paid by the company to have the paint sludge collected and treated.

4.4. Application example: Scheduling problem identification (Step 4)

Table 5 presents the process and outputs of the problem identification step.

Table 5: Waste-minimizing scheduling problem identification step

Information	Identification process	Resulting notation
Data sets	$\mathcal{I}$: set of batches to be scheduled; $\mathcal{J}$: set of operations composing a batch	$\mathcal{I}$, $\mathcal{J}$
Decision variables	s_{ij}: starting time of operation j of batch i; y_{ijkl}: 1 if operation j of batch i takes place just before operation l of batch k, 0 otherwise (operations order); t_{ij}: drying time after operation j of batch i (intermediary inventory cost); e_i: earliness of batch i, i.e. the time between the completion date and the due date of batch i (final inventory cost); nbs: nb of setups (environmental impact/cost)	Main decision variable: s_{ij}; Secondary decision variables: y_{ijkl}, t_{ij}, e_i, nbs
Workshop configuration	The painting line is the only relevant process to consider, the mask pose and finishing station have sufficient capacities and can be ignored in the scheduling problem $\rightarrow$ single machine problem	$\alpha = 1$
Constraints	Due dates d_i; sequence-dependent setup cost; Coupled tasks constraint (a_i, L, b_i) (Blazewicz et al., 2012)	$\beta = d_i, (a_i, L, b_i)$, *dependent setup-cost*
Objective functions	z_{envir}: minimize waste from eq. (2) and (3) $z_{\text{envir}} = s_{w_1} \times nbs_1 \times ((c_{r_3} + (1 - r_{r_3}) \times (1 - c_{r_3}))$; z_{eco}: minimize waste and inventory costs $z_{\text{eco}} = nbs_1 \times set_{c_1} +$ inventory cost (intermediary, final)	$\gamma = \min(z_{\text{envir}}, z_{\text{eco}})$

The main decision variable is the starting time of each operation s_{ij}, which is the primary way of improving the objective functions. Secondary decision variables such as the number of setups or the drying time also affect the objective functions, but are dependant on the main decision variable. The α, β and γ fields are obtained sequentially using all the previous information. It is to be noted that the objective functions z_{envir} and z_{eco} only comprise terms of equations (2)-(3) and (7)-(8) that are affected by the decision variables. From this problem definition step, the work can be carried on to fully model the scheduling problem. A mathematical representation of this problem using MILP can be found in Le Hesran et al. (2018). A commercial solver was then used to find alternative schedules providing trade-offs between inventory cost and waste generation. Further numerical experiments using both linear programming and a genetic algorithm have shown that setup-related waste could be reduced up to 36% at the expense of a 13% increase in inventory.

5. Discussion

This case study provides some feedback as to how this methodology should be implemented and how it can promote waste-reduction in scheduling. In the following paragraph, several points are discussed and perspectives identified.

5.1. Data collection

The most salient difficulty resulting from this application case is the issue of data collection and interpretation. This includes information on operational parameters, costs or waste management which are often not directly available and need to be either collected on-site or extrapolated from existing data. This is especially relevant for environmental costs (treatment and collection costs) which are often considered as overheads, or the waste generated by single quantity centers which is aggregated into larger groups. This issue can be addressed by using appropriate data collection techniques such as described in the ISO 14033 (2012). As a hybrid method between flow assessment, LCA and scheduling, this methodology requires input from different actors, which can be complex to combine. It is important to carefully prepare interviews with personel (QHSE and production managers, operators) as they are directly involved in the production process. To facilitate its implementation, the first step is especially useful in narrowing the study scope and reducing the necessary calculations for costs and environmental impacts. One should also remember that some of the data used represents averaged values (daily production, daily waste output, ...). Unforeseen events such as machine breakdowns are not explicitly considered although they can have large impacts on both environmental and economic performance. Including these events in the scheduling problem modeling could enable the use of environmentally robust schedules.

5.2. Energy and gaseous emissions

As stated in Section 3.1, neither energy consumption nor gaseous emissions are considered in this methodology. As a result, only physical flows are included when assessing both costs and environmental impacts (e.g. the LCA is carried out on the used resources and end-of-life treatment of waste, and not on the energy used during processes). This could certainly be an extension to this methodology, especially when considering the work already devoted to energy flow assessment (Liu et al., 2018) and energy efficient scheduling (Giret et al., 2015). Some processes can also emit gaseous pollutants such as Volatile Organic Components (VOCs) or nitrous and sulphur oxides which can have great environmental impacts. In the application case example, reducing paint sludge generation might also reduce VOC generation, which is a further incentive to implement waste prevention techniques. However, this would lead to an increased complexity at all steps of the methodology, requiring more data collection and impact assessment, with an increased number of decision variables and objective functions. In some cases, the same decision variables are involved in reducing both waste generation and energy consumption (in the case of turning on some machines for example). It then seems appropriate to consider both energy and waste at the same time, as it does not greatly increase the problem complexity. Otherwise, separating the energy consumption and waste reduction scheduling problems might be necessary.

5.3. Product system improvement

As this methodology's purpose is to identify waste reduction opportunities through scheduling, each of its step provides relevant information to the decision maker. Step 1 characterizes the product system and subsystem, and gives estimated impacts for each. This information can be used to identify the most impacting ones, and improvement measures can be devised even though no scheduling considerations are involved (e.g. process improvement, product design, materials replacement ...). Step 2 provides the standard information on flows circulating within the system, but the parametric representation allows for more precision in identifying which quantity center/parameter is actually responsible for waste generation. This can serve as a basis for operational adjustments beyond the use of scheduling. Step 3 enables the identification of cost drivers in waste flows, which is especially relevant when these costs tend to be underestimated or misattributed. Using this information, decision-makers can make more informed choices and can be incentivized to reduce their waste generation after realizing their actual cost. Finally, step 4 provides a complete description of the waste-minimization scheduling problem at hand. This information can be used to accurately model the problem using mathematical representation, and facilitate subsequent solving through the use of exact or approached methods. Simulating alternative production scenarios or drawing future-state maps such as the ones used in VSM are also effective ways to facilitate decision-making. It is important to note that each step of this methodology can be viewed not only as part of a process but also as an end by itself, providing useful information even if the methodology is not fully carried out due to lack of data or resources for example.

6. Conclusion

This paper presents a new four-steps methodology for the identification of waste-conscious scheduling problems using flow control, facilitating their mathematical modeling. A literature review highlights the lack of dedicated tool regarding this issue, and four methodological steps are proposed. An application case of hubcap manufacturing serves to demonstrate its applicability and results. After defining the study scope, the product system is decomposed into independent subsystems. Environmental and economic impacts are estimated and the best subsystem to study chosen. Using the operational information gathered in the first step, a parametric flow inventory is conducted, providing a full description of material flows using the production parameters. An assessment of the waste flows is then made to identify possible improvements using scheduling. In the final step, a three field notation of the associated scheduling problem is provided and relevant data and decision variables identified. This results in a complete characterization of one or more subsystem which includes monetary, environmental and scheduling-related information. While more case studies need to be carried out to further validate and improve this methodology, it has proven to be effective in identifying a scheduling problem with waste minimization concerns and given a basis for a full problem modeling. Results from flow assessment calculations show that hazardous waste generation could be reduced by 10% through appropriate scheduling. Meanwhile, numerical experiments carried out on the scheduling problem presented in the application case have shown that efficient trade-off solutions can be reached to substantially reduce waste generation with a low increase in inventory. For researchers, it is a new application of flow assessment oriented towards scheduling and waste minimization. For practitioners, it provides a comprehensive methodology to detect waste reduction opportunities within production systems. For future considerations, the inclusion of energy consumption and gaseous emissions would serve to expand its scope and potential applications, and so would including the social dimension. Another consideration is the redaction of data collection protocols which will facilitate the methodology implementation and increase its accuracy. This should hopefully foster the development and solving of environmentally-conscious scheduling problems.

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