Using flow assessment to identify a scheduling problem with waste reduction concerns: a case study

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Abstract

This paper proposes a first insight on how flow assessment can support the identification and modeling of waste-minimizing shop-floor scheduling problems. Using relevant elements from existing flow assessment methods, a four-step methodology is devised. After an overview of the different steps, a case study of hubcap manufacturing is conducted. The outcome of this case study is an identified scheduling problem with clearly defined constraints, objectives and parameters. The economic and environmental impacts are both quantified, and decision variables for problem solving are provided.

Keywords: Scheduling, Flow control, Waste minimization

Introduction
In the arising context of resource scarceness and environmental issues, new tools are being developed in order to promote greener manufacturing methods. Part of this endeavor involves flow assessment, which studies how resource flows (be they materials or energy) circulate within a production system and how they are consumed at the operational level. 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 at the operational level

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has traditionally been done bearing only economic objectives in mind, such as production costs or profit (Fang et al. 2011, Giret et al. 2015). A review of scheduling problems involving waste minimization is done in Le Hesran et al. (2019). Providing environmental information linked to operational parameters would facilitate the integration of environmental aspects into the modeling of scheduling problems. Thus, this works focuses on the following research question: how can flow assessment support the identification and modeling of waste-minimizing shop-floor scheduling problems? To answer this question, a methodology is proposed and tested on an application case of hubcap manufacturing. Firstly, an overview of the current literature on flow assessment is done and the methodology steps are described. Secondly, a practical case is presented. Finally, conclusions are drawn in the last section.

Literature review

Several flow assessment methodologies were reviewed and their focus on environmental or economic assessment and decision level (strategic, tactical, operational) determined. The analysis of these methodologies, which come from various sources (Jasch 2003, 2009, Enrico Cagno et al. 2012, Gould et al. 2016, Vinodh et al. 2015, Schubert et al. 2011, Smith & Ball 2012) and are grouped in Figure 1, highlights the lack of environmentally oriented flow assessment tools for production scheduling.

Only five consider at the same time economic and environmental criteria as well as the operational decision level – and 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) (Integrated FM) include production schedules in their model, and only Gould et al. (2016) (MFAM) use production scheduling to improve the environmental performance, although economic performance is not considered in the results. However, 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. For instance, Life Cycle Assessment (LCA) has well-tried guidelines for defining the perimeter of a study and allocation methods for environmental impact assessment. Similarly, Material Flow Cost Accounting (MFCA) is broadly used for material flow inventory applications, both on environmental and economic aspects. From the operational point of view, the Input Throughput Output (ITO) method is effective in describing process parameters.

Thus, while flow assessment is a promising tool in order to promote waste-minimization through scheduling, no dedicated methodology for this specific purpose exists as yet.

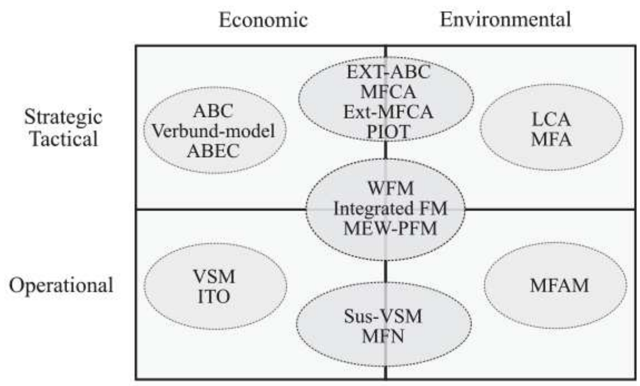

Figure 1 – Methodologies grouping according to their included criteria and decision-level

Therefore, a new approach for facilitating the identification and modeling of waste-minimizing scheduling problems is proposed.

Methodology overview

Based on the results of the literature review and the insight provided by the existing studies, a four step methodology is devised. Rather than creating an entirely new framework, it combines relevant parts of current flow assessment tools in order to answer our research question. The four steps are represented in Figure 2.

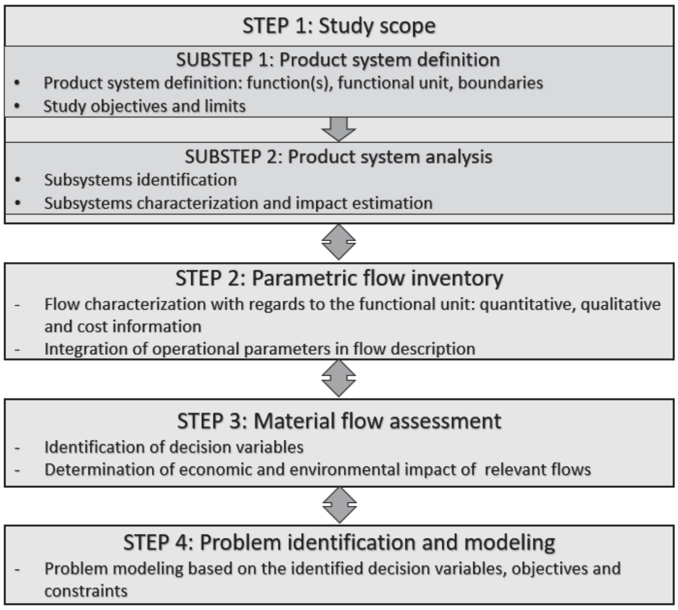

Figure 2 – Proposed methodology implementation steps

Step 1 serves to define the scope of the study, system and subsystems considered. Substep 1 is carried out similarly to the methodology proposed by the *Environmental management - Life cycle assessment - Principles and framework* (n.d.) for LCA, and the following items should be clearly identified and defined: boundaries and function of the system; functional unit; objective of the study; data requirements; assumptions and limitations regarding the study. Then, Substep 2 focuses on finding the most relevant subsystems – i.e. the groups of processes which have independent scheduling problems – to focus on. All the quantity centers (transformation, storage or transportation processes) are characterized using the ITO methodology (Schubert et al. 2011). Thus, their operating parameters related to scheduling, costs or waste are identified. Then, an estimation of the environmental impact is done for each subsystem using an LCA software. Adequate environmental indicators should be chosen depending on the waste type, surrounding ecosphere of the system and decision-maker preferences. The economic cost is determined using the Activity Based Environmental Costing (ABEC) method (Enrico Cagno et al. 2012). All situations where scheduling within a subsystem can influence waste generation should be listed, as these are the levers that will be used later on to improve the subsystem performance. The subsystems are then ranked by the decision makers, and the ones considered most important are further studied in the following steps.

In Step 2, a parametric flow inventory is carried out. Using the ISO 14051 (2011) framework, all the input, intermediary and output flows of the subsystems are defined. Using the operating parameters identified in the previous step, each flow can be quantified as a function of these parameters and the primary input flows entering the subsystem.

Proceeding in a downhill manner results in final output flows expressed according to the parameters of all the quantity centers they have crossed, or "parametric assessment".

Step 3 is the material flow assessment, where the waste output flows are characterized. Their environmental and economic evaluation is carried out, and their parametric representation is studied to identify how each parameter affects it. 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 the parameters that can influence both scheduling and the quantity of waste.

Finally, in step 4 the scheduling problem is identified and modeled. From step 3, we know which scheduling parameters can be influenced to improve the system, i.e. what the decision variables for the scheduling problem are. Results from steps 1 and 2 regarding the system and subsystems yield information on the workshop configuration (α) and the constraints on production (β). Additionally, knowledge on the different waste flows and their associated costs gives us information on the possible environmental and economic improvements, i.e. the objective functions of the scheduling problem (γ). It then becomes possible to determine the problem's three field notation ($\alpha|\beta|\gamma$) which is the common representation for scheduling problems (Pinedo 2008) as well as the decision variables that are used to solve it.

Case study

To illustrate the methodology, a practical application is carried out. This case involves a French hubcap production plant which includes raw plastic reception, oven drying, injection moulding, painting, quality control and expedition. The different steps of the methodology are successively applied in order to validate its feasibility.

Step 1: Study scope

The production of the hubcap manufacturing plant ranges from raw materials reception and preparation to the expedition of finished products. In Substep 1, the product system consists in the whole production site, including all storage facilities for materials, products and waste. In order to gather information on the system, a survey was sent to the person responsible for production (Le Hesran, Corentin 2019), and a plant visit conducted. The production is composed of products grouped into three main families: plastic pieces, unicolor hubcaps and bicolor hubcaps. Additionally, stringent requirements placed on automotive parts suppliers places each batch of hubcap under a hard due date constraint. The functional unit (FU) chosen is the production of one day's worth of hubcaps, as the production schedule is determined on a daily basis. An average of 250 workdays per year was used in this study. 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. The spatial boundary considered for this product system is represented in Figure 3. Since due dates are involved, the temporal boundary for production is set as the last due date of the lots to be produced.

After having described the product system in its entirety, Substep 2 focuses on each independent subsystem to estimate their cost and impact, as well as the potential to mitigate these impacts using scheduling. As can be seen from the product system description in Figure 3, the plant is divided into three main workshops, namely the preparation, moulding, and painting/finishing. 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 the plastic pieces and raw hubcaps, and includes injection moulding machines, an assembly post as well as a quality control post. Its waste generation sources are residual plastic coming from the injection presses, and scrapped products from the quality control. From a scheduling perspective, waste production is impacted by changes in plastic compositions for the different pieces, as the machines need to be purged each time a different type of plastic is used.

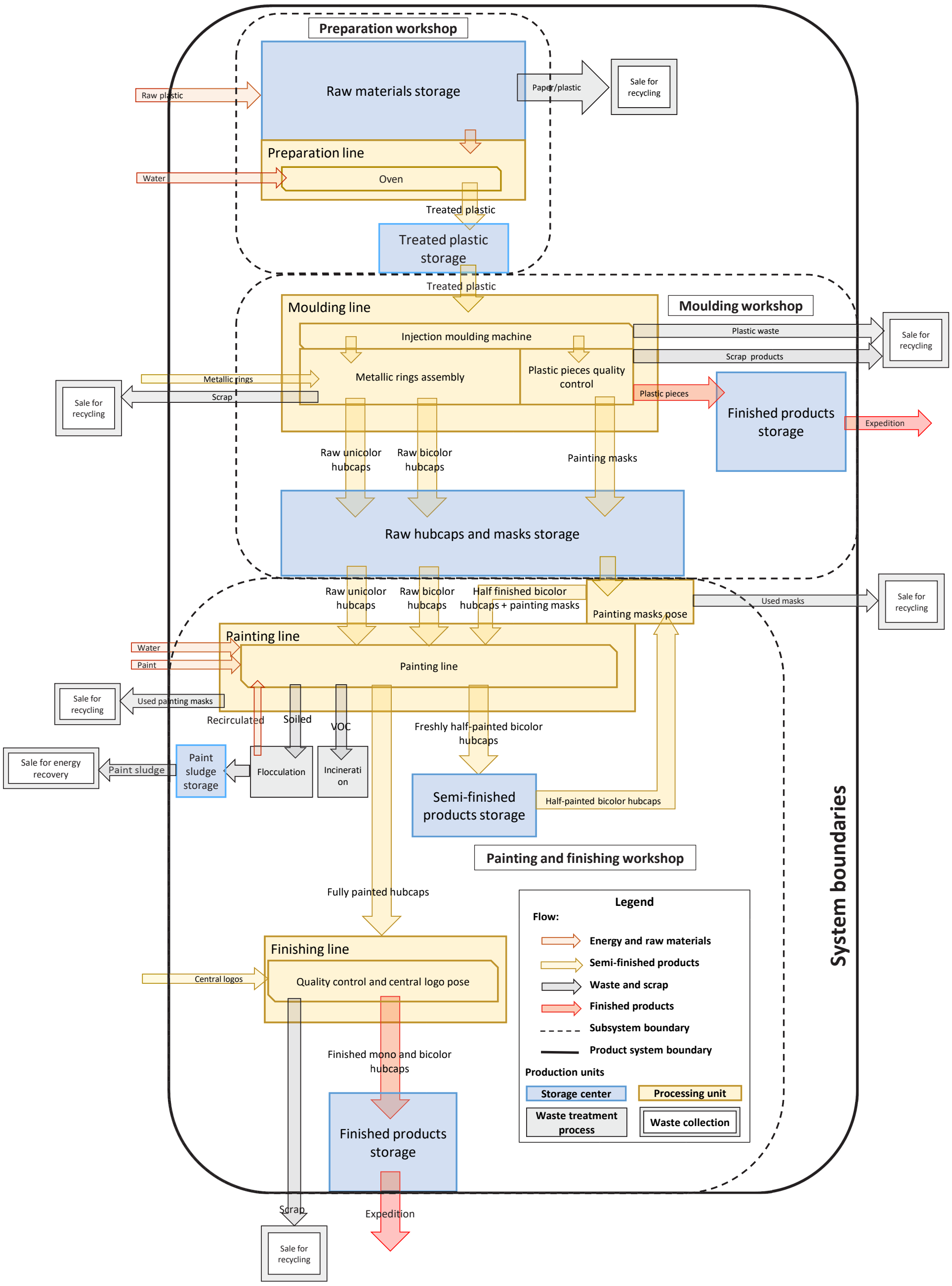

Figure 3 – Hubcap product system description

Once produced, the raw hubcaps and 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 (Code de l'environnement - livre V 2011) 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. Similarly to what occurs in the moulding workshop, scheduling impacts the waste generation through the number of required setups, i.e. color changes. Thus, the moulding and the painting/finishing subsystems have been identified as opportunities for reducing waste through scheduling. In order to gather information on these subsystems and waste management, an interview was conducted with a Quality, Hygiene, Safety and Environment (QHSE) manager using another more detailed survey (Le Hesran, Corentin 2019). 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 do not have any renting cost. 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 2017), while the price for one ton of ready-to-use paint is estimated to 3000 euros. Operating prices were calculated based on the workforce of each workshop (The Boyd Company, Inc. 2019).

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 & 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, emissions levels of paint sludge are currently compliant. They are however a concern regarding the ISO 14001 certificate renewal.

Table 1 lists the information 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. LCIA method used is the eco-indicator 99, with three aggregated indicators (total ecosystems, total human health and total resources) for better clarity. As can be seen from Table 1, paint sludge has a larger environmental impact as well as a higher economic cost. Additionally, 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 1 – Subsystems ranking: moulding and painting workshop wasteflows

	Impact	Scrap Plastic	Paint Sludge
Environmental	Material intensity	216 kg per FU	480 kg per FU
	Ecosystems (PDF × m^2 × year)	0,208 per FU	4,56 per FU
	Human health (DALY)	0,27 per FU	6,62 per FU
	Resources (MJ surplus)	1,0 per FU	36,96 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

Step 2: Parametric flow inventory
The quantity centers contained in the painting and finishing workshops are:

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

In order to characterize those quantity centers, the ITO method was applied to each of them. The indices corresponding to each parameter are shown in Table 2, and the detailed painting and finishing subsystem flow inventory shown in Figure 4.

Table 2 – 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 $$z_1 = c_{r_3} \times ((x_1 + x_2) \times o_{w_1} + nbs_1 \times s_{w_1}) \quad (1)$$

Wastewater $$z_2 = (1 - r_{r_3}) \times (1 - c_{r_3}) \times ((x_1 + x_2) \times o_{w_1} + nbs_1 \times s_{w_1}) \quad (2)$$

Used masks $$z_3 = x_2 \times (1 - s_{r_1}) \times o_{w_6} \quad (3)$$

Scrapped products $$z_4 = x_1 \times s_{r_1} + x_2 \times s_{r_1}^2 \quad (4)$$
$$z_5 = x_1 \times (1 - s_{r_1}) \times s_{r_4} + x_2 \times (1 - s_{r_1})^2 \times s_{r_4} \quad (5)$$

Thus, the parametric representation allows us to quantify each flow circulating in the subsystem as an equation of the input flows and the operating parameters of the quantity centers. In addition, cost information is also represented, and will be used in the next flow assessment step.

Step 3: Material flow assessment
After having quantified all the flows, their respective impacts and costs can be determined. More specifically, focus is given to the elementary output flows of waste, as those are the main factors to improve the environmental impact of the subsystem.

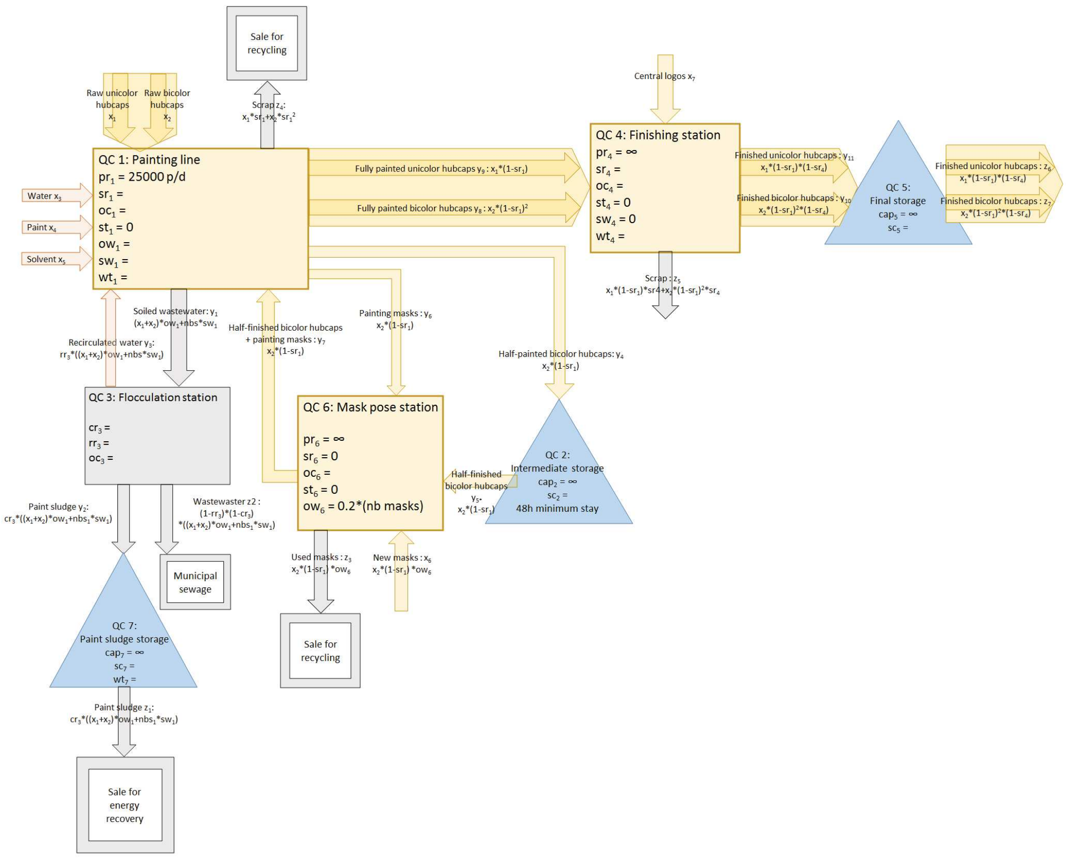

Figure 4 – Painting and finishing subsystem flow inventory

Looking at the equations (1)-(5) it can be seen that only the output flows z_1 and z_2, respectively paint sludge and wastewater, are affected by the number of setups. 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. While the number of setups does not appear in any other flow from the subsystem, it still affects the rest of production at the operational level in terms of lot-sizing. 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. Thus, 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.

Based on the different activities and cost drivers described in the Ext-ABEC method (Enrico Cagno et al. 2012), the detailed cost equations of flows z_1 and z_2 are:

$$c_{z_1} = m_{c_1} \times z_1 + c_{r_3} \times o_{c_3} \times y_1 + c_{r_3} \times nbs_1 \times set_{c_1} + s_{c_7} \times y_2 + wt_{c_7} \times y_2 \tag{6}$$
$$c_{z_2} = m_{c_2} \times z_2 + (1 - c_{r_3}) \times o_{c_3} \times y_1 + (1 - c_{r_3}) \times nbs_1 \times set_{c_1} \tag{7}$$

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

- $m_{c_1} \times z_1$: material cost of z_1, depends on the cost 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;
- $c_{r_3} \times nbs_1 \times set_{c_1}$: setup cost for the painting line;
- $s_{c_7} \times y_2$: storage cost for the paint sludge;
- $wt_{c_7} \times y_2$: waste collection and treatment cost.

Step 4: Scheduling problem identification and modeling

Table 3 presents the process and outputs of the problem identification and modeling step.

Table 3 – Problem identification and modeling process

	Identification process	Resulting notation
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. (1) and (2) $s_{w_1} \times nbs_1 \times ((c_{r_3} + (1 - r_{r_3}) \times (1 - c_{r_3}))$; z_{eco}: minimize waste and inventory costs $nbs_1 \times set_{c_1} +$ inventory cost (intermediary, final)	$\gamma = \min(z_{\text{envir}}, z_{\text{eco}})$
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: $y_{ijkl}, t_{ij}, e_i, nbs$

The α and β fields (workshop configuration and scheduling constraints) can be determined based on the information gathered during steps 1 and 2. The γ field (objective function) is identified during step 3 by considering all waste outputs and costs that can be influenced through scheduling. The data sets are determined using the information from step 1. Finally, decision variables are the production parameters that influence both scheduling and waste generation. They are first identified during substep 2, and then quantified during steps 2 and 3. After this step, the problem can be represented 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). A MILP formulation of this problem can be found in Le Hesran et al. (2018).

Conclusion

This study presents an application case for a new methodology for the identification and modeling of waste-conscious scheduling problems using flow control. After a brief literature review, a four-steps methodology was proposed and applied to a case study of hubcap manufacturing. After defining the study scope, the product system was decomposed into independent subsystems. Environmental and economic impacts were estimated and the best subsystem to study chosen. Using the operational information gathered in step 1, a parametric flow inventory was conducted, providing a full description of material flows using the production parameters. An assessment of the waste flows was then conducted to identify possible improvements using scheduling. In the final step, a three field notation of the associated scheduling problem was provided and relevant data and decision variables identified. While more case studies need to be carried out and a full framework developed for 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.

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