Heating and cooling phase scheduling algorithm for automotive curve glass production

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Abstract: The need to increase the service level of the automotive supply chain, especially after the COVID-19 pandemic, leads to an increase in the efficiency and effectiveness of the production systems. The use of scheduling techniques and their implementation in Enterprise Resource Planning (ERP)/ Manufacturing Execution System (MES) systems can be a lever towards this improvement, remarkably in particularly constrained production systems. The presented case study stems from an industrial context and focuses on the heating and cooling phases of curved glass used in the automotive sector. In particular, the glass is subjected to a gradual heating process at temperatures between 500 and 600 °C, after which it softens and adheres by force of gravity to a curved mold located on the bottom of the heated room. The cooling phase takes place very slowly, to allow the material to acquire a greater flexural strength than a normal flat glass. The objective of this study is to present a scheduling algorithm to optimize the production of the curve glasses with different technical characteristics and heating and cooling phases. The implementation of this algorithm in the industrial context permits the increase of the ovens’ saturation and the respect of the delivery date of the production orders.

Keywords: Scheduling, Ovens Saturation, Curve Glasses

I. INTRODUCTION

Car manufacturing is a global process. With suppliers, OEMs and retailers often spread across multiple continents, it is critical to find flexible solutions to supply chain relationships, which enable quick communication and the ability to purchase the right parts at the right price. While the geographical element is a challenge, especially in a period characterized by health and geopolitical crisis, integration skills can support the delivery of the flexible outcomes needed by the car manufacturers. Specifically, a solution can be the creation of stable, long-term strategic partnerships with key partners and the diversification and expansion for low added value suppliers, relying on larger numbers of fleeting supply chain engagements. In both cases, visibility, flexibility, and communication are critical to success which imply an increase of the service level of the supply chain and of each supplier.

Moreover, the diffusion of Covid-19 represented an external shock of unprecedented magnitude, affecting the supply and demand sides alike, and revealing the fragility of most supply chains [1]. Several companies around the world have experienced supply chain interruptions because of the Covid-19 outbreak, mainly caused by production disruption of raw materials and spare parts, and setbacks in logistics [2]. Hence, the pandemic increases the needs for flexibility, product availability, information sharing, and cycle times reduction. OEMs, retailers and component suppliers all need to reconsider best practices, develop more sustainable and robust supply chain relationships, and implement dynamic production planning and scheduling in enterprise resource planning (ERP) or manufacturing execution system (MES) with the support of digital technologies [3]. This huge flexibility required at each step of the supply chain poses relevant issues and complexity where rigid equipment should be used (e.g., furnaces). In many cases this complexity is externalized by suppliers and managed with specific contracts [4]

Traditionally, scheduling problem are focused on stationary processes. However, most of the real application must face uncontrollable and hard-to-predict events (e.g., order cancellations, changes in due dates, changes in production constraints, new order arrivals, rush orders). Providing an extensive literature analysis is beyond the scope of this study. However, some studies can be found that address this need for dynamicity and flexibility mainly in the iron and steel industry [5]. For instance, [6] proposed a case study focused on online and dynamic scheduling of parallel heat treatment furnaces at a manufacturing firm. [7] investigated the planning and scheduling methods for integrated steel production among which the constraints satisfaction problem is depicted as a relevant branch of artificial intelligence focused on finding feasible solutions satisfying the constraints rather than the optimal solution (which can be unfeasible). [8] approached the scheduling problem of metal alloy production in small foundries with a mixed integer programming formulation and a relax-and-fit approach.

The objective of this study is to present a scheduling algorithm for rigid processes (i.e., heating, and cooling processes) to optimize the production of curve glasses with different technical characteristics and heating and cooling phases. The solution procedure proposed will facilitate production planning and scheduling decision-making in face of uncertainty. The implementation of this algorithm in the industrial context permits the increase of the ovens' saturation and the respect of the delivery date of the production orders

The remainder of the paper is organized as follows. Section 2 introduces the problem and defines the main assumptions. Section 3 provides the heuristic scheduling model applied to the case study for maximizing the saturation of the ovens and minimizing the delay of the orders. Section 4 depicts the results coming from the application of the proposed model. Finally, Section 5 summarizes the main findings and proposes further research enabled by the current study.

II. PROBLEM AND ASSUMPTIONS

The scenario considered in this study deals with an industrial context focused on the heating and cooling phases of curved glasses used in the automotive sector. Curved glass manufacturers are strategic suppliers due to the complexity and relevance of the products which require also a large know-how posing great entry barriers to the market. Hence, few suppliers must face the demand of different car manufacturers for different car models. For each car model, a specific program is defined which includes all the parts to be produced for the car model considered. Due to the limited capacity of the ovens which represent the bottlenecks, a priority should be set for each program. A general production flow diagram of the company is presented in Fig. 1. The first production phase consists in the cutting of the glass purchased from the raw material supplier. Then, the glass sheets are shaped accordingly to the part that should be produced and some of them, if any, undergo to the automatic serigraphy and vitrification processes. Later, all the glass sheets that belong to the same part are simultaneously bended: from this point the glass sheets will be associated to a specific final part. Once bended, some of the glass sheet will be coated or chemically hardened to further improve the resistance performance of the glass. All the glass sheets are then grinded on a 5-axis machine to provide them the final shape and, if required, are painted. The different glass sheets belonging to the same final product are together assembled with additional materials (such as, layer made of polyvinyl butyral - PVB, or polycarbonate – PC). The last phases of the production process deal with the testing, the sealing (during which any accessory required is added), and the inspection of the assembled product.

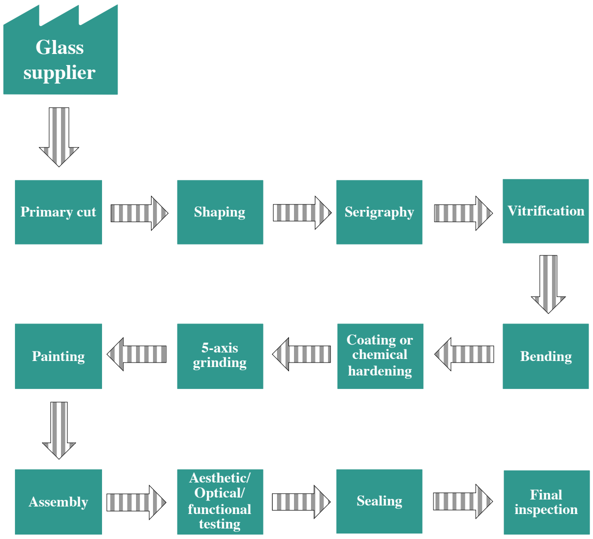

Fig. 1 General production flow diagram of the company

The huge variability foreseen from car manufacturers is amplified while moving to upstream stages, e.g., to the supplier of curved glasses. One of the main issues of curved glass producers, hence, is to face the high demand variability and the wide range of products with rigid equipment: i.e., the ovens. The glasses undergo to a gradual heating process at temperatures between 500 and 600°C after which the glass softens and adheres by force of gravity to a curved mold located on the bottom of the heated room. The cooling phase takes place very slowly, to allow the material to acquire a greater flexural strength than a normal flat glass.

In the case study, three gas ovens are used for bending the glass to produce side windows and other small glasses for different types of cars (i.e., right front side glass – FDR, left front side glass – FDL, right rear side glass – RDR, left rear side glass – RDL, right roof flap – QLR, left roof flap, QLL). Specifically, each oven can perform a cycle per day (i.e., cycle time equal to 24 hours) dedicated to a specific heating program. Hence, only products that require the same heating program can be charged in the same oven during the same cycle. Generally, products belonging to the same program (i.e., different parts of the same car) require the same heating program to be set in the oven. Moreover, there is a limited availability of tools which are product-specific since each product has a different curve shape (e.g., different positioning, angle, ...). In specific cases, it could also be possible to bend two or more glasses using the same tool: this is the case of smaller products.

Each oven consists of three levels which represent an additional constraint since not all the products can be positioned in all the levels for technological restrictions: in fact, different levels are characterized by a different temperature and heating process. Moreover, the number of tools that can be placed per level is usually 4, but this number may change depending on the products (mainly on their size).

Currently, the production planner of the ovens manually proposes a solution trying to reach the customer needs in terms of punctuality, while at the same time, produces lot to reduce the setup costs, when possible. However, this solution results in a low saturation of the ovens, and in additional issues related to delays and the management of new incoming orders requiring the bending phase.

III. MODEL

To solve the presented problem, with the objective to maximize the saturation of the ovens from one hand and to minimize the delay for the downstream production stations of the priority orders on the other hand, it has been developed a heuristic that considers all the production constraints.

The heuristic schedules the different production orders by assigning them to the different possible levels of the ovens. In Fig. 2, it is shown the flow-chart of the heuristic developed.

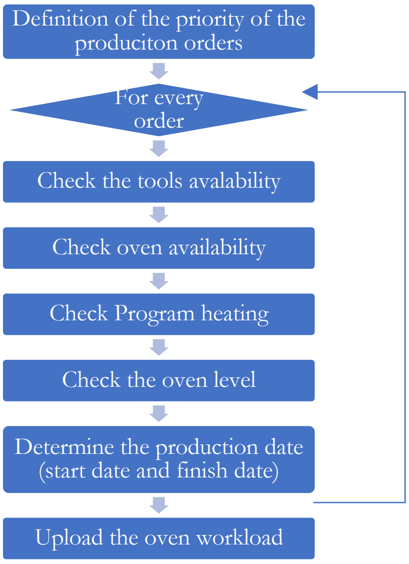

Fig. 2 Flow-chart of the heuristics

The heuristic starts from the downloading of the monthly demand exploded by the Material Resource Planning (MRP) system that assures the presence of the material necessary for the treatment. By starting from the priority of the different orders read by the information system, the heuristic reads the quantity and the production cycle information (i.e., tools, oven level, heating program, cycle time, …) of the production orders. Starting from the first order and for every order of the previous list, the heuristic executes the following checks:

- *Oven availability*: the heuristic checks when the oven is available to produce the order quantity.
- *Heating program*: if the oven is available, but other production orders are already planned, the heuristic checks whether the heating program is the same; otherwise, it is not possible to load the considered production order on the oven until the previous heating program is finished. Hence, a different oven should be used, if available.
- *Oven level*: the heuristic checks the oven level with respect to the production cycle indication; in fact, the ovens have tree levels but not all the products can be processed in all the levels for technological restrictions (i.e., some products can be processed only on level 1 and 2).
- *Number of tools per level*: the heuristic must consider the maximum number of the tools per level that depends on the product.

By considering the previous workload scheduled, the heuristic determines the possible scheduling (i.e., oven, level, start date and finish date) of the production orders considered by maximizing the saturation of the ovens, while the priority of the different orders assures the minimization of the delay of the priority orders. At the end, the heuristic sends the result to the information system for the successive dialog with the MES.

In the specific, the heuristic is developed in MS Visual Basic .Net and integrated with the information systems of the company. Fig. 3 depicts the communication system from/to the information system.

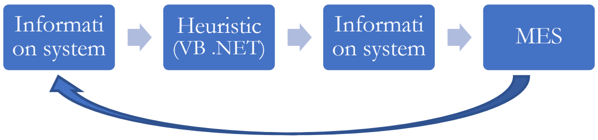

Fig. 3 Interaction between the heuristic, the information system, and the MES

IV. RESULTS

To validate the heuristic proposed, it is considered the weekly demand of one month (February) with 8 different client programs. Every client program has two or more kind of product with a specific production cycle (i.e., tool, heating program, oven levels): the scenario presented considers 26 different products. The possible heating programs are 3 and the number of tools is different with respect to the different products (in general the tools are dedicated for every product). Following, Table 1 report the demand and the constraints for the considered month for each product.

TABLE 1
DEMAND AND CONSTRAINTS FOR THE PRESENTED SCENARIO (FEBRUARY)

Products	**Program**	**Priority**	**Heating program**	**Level 1**	**Level 2**	**Level 3**	**# Tools**	**Feb**
FDL	Program 1	1	4	Y	Y	NO	3	8.25
FDR	Program 1	1	4	Y	Y	NO	3	8.25
RDL	Program 1	1	4	Y	Y	NO	3	8.25

RDR	Program 1	1	4	Y	Y	NO	3	8.25
QLL	Program 1	1	4	Y	Y	NO	3	8.25
QLR	Program 1	1	4	Y	Y	NO	3	8.25
FDL	Program 2	3	2	Y	Y	NO	2	1
FDR	Program 2	3	2	Y	Y	NO	2	1
RDL	Program 2	3	2	Y	Y	NO	2	1
RDR	Program 2	3	2	Y	Y	NO	2	1
FDL	Program 3	6	3	Y	Y	NO	1	2.5
FDR	Program 3	6	3	Y	Y	NO	1	2.5
FDL	Program 4	7	4	Y	Y	Y	1	5
FDR	Program 4	7	4	Y	Y	Y	1	5
RDL	Program 4	7	4	Y	Y	Y	1	5
RDR	Program 4	7	4	Y	Y	Y	1	5
FDL	Program 5	8	4	Y	Y	NO	1	1
FDR	Program 5	8	4	Y	Y	NO	1	1
RDL	Program 5	8	4	Y	Y	NO	1	1
RDR	Program 5	8	4	Y	Y	NO	1	1
FDL	Program 6	9	2	Y	Y	NO	1	2
FDR	Program 6	9	2	Y	Y	NO	1	2
RDL	Program 6	9	2	Y	Y	NO	1	2
RDR	Program 6	9	2	Y	Y	NO	1	2
FDL	Program 7	10	3	Y	Y	Y	1	1.25
FDR	Program 7	10	3	Y	Y	Y	1	1.25
FDL	Program 8	14	3	Y	Y	Y	1	1.25
FDR	Program 8	14	3	Y	Y	Y	1	1.25
RDL	Program 8	14	3	Y	Y	Y	1	1.25
RDR	Program 8	14	3	Y	Y	Y	1	1.25

This simulation considers three ovens where every oven has three levels for the treatment of the different products. Specifically, every product considered has a cycle time equal to 24 hours and needs one tool. In Table 2, it is reported the maximum number of tools per level per program.

TABLE 2
MAXIMUM TOOLS NUMBER PER LEVEL PER PROGRAM

Program	# Tools per level
1	4
2	4
3	2
4	4
5	4
6	2
7	2
8	2

Following, Table 3 reports the tools scheduling of the three ovens during the week. Specifically, for every oven it is reported for every day the level and the heating program with the indication of the total number of allocated tools. To maximize the saturation, the heuristic tray to maximize the number of tools per level by respecting the different constraints. Table 4 reports the resulting weekly saturation per oven and per level.

TABLE 3
RESULTING SCHEDULING FOR MAXIMIZING THE SATURATION OF THE OVEN

Oven	Programm Heating	Level	Quantity	Program	Part	Day
1	4	1	3	1	FDL	1
1	4	1	1	1	FDR	1
1	4	2	2	1	FDR	1
1	4	2	2	1	RDL	1
2	4	1	1	1	RDL	1
2	4	1	3	1	RDR	1
2	4	2	3	1	QLL	1
2	4	2	1	1	QLR	1
3	4	1	2	1	QLR	1
1	4	3	1	4	FDL	1
1	4	3	1	4	FDR	1
1	4	3	1	4	RDL	1
1	4	3	1	4	RDR	1
3	4	1	1	6	FDL	1
3	4	1	1	6	FDR	1
3	4	2	1	6	RDL	1
3	4	2	1	6	RDR	1
1	4	1	3	1	FDL	2
1	4	1	1	1	FDR	2
1	4	2	2	1	FDR	2
1	4	2	2	1	RDL	2
2	4	1	1	1	RDL	2
2	4	1	3	1	RDR	2
2	4	2	3	1	QLL	2
2	4	2	1	1	QLR	2
3	4	1	2	1	QLR	2
1	4	3	1	4	FDL	2

1	4	3	1	4	FDR	2
1	4	3	1	4	RDL	2
1	4	3	1	4	RDR	2
1	4	1	3	1	FDL	3
1	4	1	1	1	FDR	3
1	4	2	2	1	FDR	3
1	4	2	2	1	RDL	3
2	4	1	1	1	RDL	3
2	4	1	3	1	RDR	3
2	4	2	3	1	QLL	3
2	4	2	1	1	QLR	3
3	4	1	2	1	QLR	3
1	4	3	1	4	FDL	3
1	4	3	1	4	FDR	3
1	4	3	1	4	RDL	3
1	4	3	1	4	RDR	3
1	2	1	2	2	FDL	4
1	2	1	2	2	FDR	4
1	2	2	2	2	RDL	4
1	2	2	2	2	RDR	4
2	3	1	1	3	FDL	4
2	3	1	1	3	FDR	4
3	4	1	1	4	FDL	4
3	4	1	1	4	FDR	4
3	4	1	1	4	RDL	4
3	4	1	1	4	RDR	4
2	3	2	1	7	FDL	4
2	3	2	1	7	FDR	4
2	3	3	1	8	FDL	4
2	3	3	1	8	FDR	4
1	3	1	1	3	FDL	5
1	3	1	1	3	FDR	5
2	4	1	1	4	FDL	5
2	4	1	1	4	FDR	5
2	4	1	1	4	RDL	5
2	4	1	1	4	RDR	5
3	2	1	1	6	FDL	5
3	2	1	1	6	FDR	5
3	2	2	1	6	RDL	5
3	2	2	1	6	RDR	5
1	3	2	1	8	RDL	5
1	3	2	1	8	RDR	5
1	3	1	1	3	FDL	6
1	3	1	1	3	FDR	6
2	2	1	1	6	FDL	6
2	2	1	1	6	FDR	6
2	2	2	1	6	RDL	6
2	2	2	1	6	RDR	6

TABLE 4
OVEN TOOLS WEEKLY SCHEDULE

	Day					
	1	2	3	4	5	6
Oven 1	**4.0**	**4.0**	**4.0**	**2.7**	**1.3**	**0.7**
Level 1	4.0	4.0	4.0	4.0	2.0	2.0
Level 2	4.0	4.0	4.0	4.0	2.0	0
Level 3	4.0	4.0	4.0	0	0	0
Oven 2	**2.7**	**2.7**	**2.7**	**2.0**	**1.3**	**1.3**
Level 1	4.0	4.0	4.0	2.0	4.0	2.0
Level 2	4.0	4.0	4.0	2.0	0	2.0
Level 3	0	0	0	2.0	0	0
Oven 3	**2.0**	**0.7**	**0.7**	**1.3**	**1.3**	**0**
Level 1	4.0	2.0	2.0	4.0	2.0	0
Level 2	2.0	0	0	0	2.0	0
Level 3	0	0	0	0	0	0

It is possible to observe that, given the specific production constraints, the total number of tools decreases during the week, and, hence, it is necessary to use six days (the sixth day is considered overtime) in order to satisfy the demand, although some levels are not full. By using the heuristic proposed the average saturations of the ovens increases of 8,2% (from 72,3% to 80,5%).

V. CONCLUSIONS AND FUTURE RESEARCH

The presented study focuses on a particularly constrained scheduling problem. Specifically, the industrial case concerns the heating and cooling phases of curved glass used in the automotive sector. The objective of this study was to present a scheduling algorithm for the optimization of the production of curve glasses with different technical characteristics and heating and cooling phases. The implementation of this algorithm in the ERP system allowed the increase of the ovens’ saturation and the respect of the delivery date of the production orders. Possible developments foresee two different directions: 1) the use of metaheuristics for the solution of larger problem sizes (currently heuristic is of the greedy type and responds correctly to business needs, but an increase in the size of the problem could significantly increase the computational time) 2) since ovens require a huge amount of energy (as process energy, as energy for auxiliary systems), the manufacturing of glass is an energy-intensive process

[9] [10], hence, making the energy costs related to the glass treatment process explicit in the objective function could raise the relevance of increasing the ovens' saturation. In this way, increasing the saturation can represent a managerial energy efficiency measure, which result in low cost energy savings and also in a reduction of the environmental impacts [11,12].

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