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Hybrid flow shop rescheduling for contract manufacturing services

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ABSTRACT

Several approaches for strategic and tactical integration of supply chains considering the demand management process have been proposed in the literature. However, in the context of Industry 4.0, there is a lack of studies related to the scheduling and rescheduling process integrating industries on the operational level. This paper proposes a novel hybrid flow shop rescheduling procedure to address the integration, on the operational level, of a contract manufacturer, who handles production execution and inventory control, and their industrial customers, who are in charge of the delivery planning process. The research question emerged from the empirical problem of connecting a contract manufacturer with its industrial customers. In alignment with the findings in the literature review, based on an updated conceptual model, a real hybrid flow shop was modelled using a multi-method approach that combines discrete event and agent-based simulation. The results show improvements in overall production and delivery performance. One can say that this is the first time that a production rescheduling problem is handled considering industries' integration at the operational level. Even though the primary motivation of this research was to solve a production rescheduling issue in a Contract Manufacturer, the developed approach allows application in any B2B partnership.

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Production rescheduling; reactive scheduling; multi-method modelling; multi-agent system; B2B; contract manufacturing service

1. Introduction

Production rescheduling embraces changes or updates in an existing schedule driven by internal or external issues. These challenging issues have been reviewed by several authors: Suresh and Chaudhuri (1993); Raheja and Subramaniam (2002); Vieira, Herrmann, and Lin (2003); Li and Ierapetritou (2008); Ouelhadj and Petrovic (2009); Cardin et al. (2017); as well as Uhlmann and Frazzon (2018).

Since the 1950s, many research studies have been developed to conceive methods capable of dealing with production schedule problems (Gomes, Barbosa-Póvoa, and Novais 2010). In 1993, Maccarthy and Liu (1993) highlighted the gap between scheduling theory and practice. Although several efforts to study new solutions for dynamic scheduling, most with theoretical experiments, the lack of researches with practical applications in real industries is still a fact (Uhlmann and Frazzon 2018).

Staughton and Johnston (2005) describe business-to-business (B2B) relationships as crucial for efficient and effective operations. Additionally, for Magyar (2018), one of the contract manufacturers' strategies is to disregard partners as independent companies. In reality, despite contractual agreements among enterprises, many issues are solved based on common sense supported by good one-to-one relationships. Thus, this statement is particularly true for unforeseen events. Therefore, production disruptions from the manufacturer side and delivery changes from the customer side usually trigger the negotiation of the delivery plan between two industries. This event can even occur within a frozen period, in which delivery changes are not allowed due to contractual agreements.

Several approaches for strategic and tactical integration of supply chains considering the demand management process have been proposed in the literature. However, in the context of Industry 4.0 initiatives (Kagermann et al. 2013) there is a lack of studies related to the scheduling and rescheduling process integrating two or more industries on the operational level (Uhlmann and Frazzon 2018). Luo et al. (2017) state that operational level decisions regarding production and logistics are taken independently by each involved company.

The present research was inspired by issues experienced by the authors in real situations, motivating an empirical research approach. The project was developed

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in five steps. Firstly, considering production rescheduling praxis based on delivery plan negotiation and the lack of academic literature about industrial integration at the operational level, the need for research efforts addressing rescheduling approaches with industrial integration was identified. The next step consisted of a literature review conducted to investigate any new research about rescheduling integrating industries and to find the most proper approach to handle the issue. After that, a conceptual model was updated to propose a viable solution for the problem. Following that, the chosen approach was applied in a simulation model built upon empirical data collected from a real case. Thus, the performance of the approach could be analysed. Finally, the results were discussed to address the research question.

Hofmann and Rüsch (2017) referred to 'smart manufacturing' and 'integrated industry' as some of the names for Industry 4.0. Moreover, they stated that system elements make autonomous decisions in value networks that are controlled in a decentralised manner. According to Rossit, Tohmé, and Frutos (2019), what differentiates industry 4.0 is the adoption of interconnected autonomous agents. Additionally, for Khan, Chaabane, and Dweiri (2019) to ensure rapid product delivery and more flexibility, fast decision based on real-time data is essential.

Kusiak (2018) defines six pillars of smart manufacturing: manufacturing technology and processes; materials; data; predictive engineering; sustainability and; resource sharing and networking. The ones that are mostly related to this research are: predictive engineering and resource sharing and networking. The first represents a new paradigm of constructing digital representations of the phenomena of interest to support decisions. The second consists in much of the creative and decision-making activities that will take place in the digital space.

One of the most common production environments found in reality is the Hybrid Flow Shop (HFS). In this category of production system, two or more workstations are arranged in series. Therefore, in order to reduce the impact of the bottleneck, each one of them could have identical parallel machines or devices to increase the capacity and balance the production (Naderi, Gohari, and Yazdani 2014). The jobs in Unidirectional HFS follows the standard sequence, from the first stage to the last stage (Choi, Kim, and Lee 2011).

The Flexible Manufacturing System (FMS) is designed to produce several products in the same system. Moreover, the Reconfigurable Manufacturing System (RMS) is designed to quickly adjust its production capacity, considering both hardware and software, in case of market or regulatory requirements changes. Koren et al. (1999) detail both manufacturing systems.

The gap about rescheduling process integrating two or more industries on the operational level (Uhlmann and Frazzon 2018) and the conceptual model presented as an alternative to solve this gap (Uhlmann et al. 2018) substantiated the initial motivation of this research to solve a production rescheduling issue in a Contract Manufacturer. This paper proposes a novel HFS rescheduling procedure to address the integration of manufacturing services and their industrial customers in dynamic contexts. Since the model is dealing with operational level problems, the factory planner is released to focus on tactical and strategic scheduling issues. Additionally, this research considers a manufacturer with FMS that uses equal and reconfigurable parallel devices in its bottleneck workstations. A test case was applied using multi-method modelling, combining discrete-event and agent-based modelling.

2. Theoretical frame

2.1. Hybrid flow shop rescheduling

Uhlmann and Frazzon (2018) summarise production rescheduling as 'the process of updating production schedule', which is often triggered by unexpected disruptions (Vieira, Herrmann, and Lin 2003; Huang et al. 2005; Dong and Jang 2012). HFS have been studied since 1950s (Johnson 1954). A simple flow shop system is composed of stages, in which a set of jobs are processed following the same flow direction. In order to increase production capacities in a flow shop system, a common practice is parallelising machines at bottleneck stations. The systems with two or more stages in series with one or more parallel machines at each stage are called hybrid flow shop (Linn and Zhang 1999; Ribas, Leisten, and Framiñan 2010; Ruiz and Vázquez-Rodríguez 2010; Choi, Kim, and Lee 2011; Chen, Li, and Ma 2017). Fan et al. (2018) simplify HFS definition as 'combination of more than one classical shop scheduling, such as flow shop scheduling, job shop scheduling, open shop scheduling, parallel machine scheduling, and multiprocessor task scheduling'. This research handles a production rescheduling model applied to a hybrid flow shop system, combining flow shop and job shop.

2.2. Industrial integration and practical applications

Uhlmann and Frazzon (2018) identified the need for praxis-oriented research, as well as the need of research efforts related to industrial integration at the operational level. Their review research considered papers published until February/2018. To analyse changes in their results, a new review was performed, following the same paper collection criteria proposed by them:

- Articles, conference papers and proceeding papers of Engineering area, published in 2018 and 2019, written in English, were collected from databases Scopus and Web of Science, using the Boolean logic ('production rescheduling' or 'manufacturing rescheduling' or 'reactive scheduling' or 'schedule recovery' or 'schedule repair');
- It was analysed papers that are explicitly and specifically dedicated to production rescheduling with full text available;
- It was not analysed papers, which production rescheduling is only used for a specific application area, such as: oil operations, gas industry, thermal power, airline schedule, flight schedule, aircraft operations, nurse schedule, power systems, electricity market, energy systems, wind turbines, marine machinery, water distribution, gas refinery, oil refinery, fuel systems, remanufacturing operations, holonic manufacturing systems, air traffic, air transportation, construction processes, concrete structures, chemical processes, bus transportation, vehicle routing, train schedule, shipping operations, project scheduling, maintenance schedule, life cycle studies, steel industry, iron industry and fibre industry.

In this complementary review, one can conclude that the need for praxis-oriented research, is still a fact since the results only show papers with computational experiments (Chen, Deng, and Wang 2018; Valledor et al. 2018; Yang and Gao 2018).

Ivanov, Dolgui, and Sokolov (2018) report a scheduling recovery model subject to disruption in material flows presenting interrelation among schedule, resources and recovery actions and integrating supplier, factory and warehouse. They combined two research areas: design resilience assessment and robust scheduling. Their study is an extension of the supply chain scheduling (Ivanov and Sokolov 2012) and resilience analysis by an explicit integration of the optimal schedule recovery policy and supply chain resilience. Ivanov and Sokolov (2012) analyse a supply chain that is planned and scheduled considering the supply chain optimisation as a whole, reflecting the ideology of supply chain management. In their model, the solution may be considered as an orientation for schedule changes concerning local enterprise goals.

Uhlmann et al. (2018) present a conceptual model to reschedule the production orders of a manufacturer considering the information and decisions from an industrial customer.

The scheduling recovery model proposed by Ivanov, Dolgui, and Sokolov (2018) dealt with an ideal supply chain, proposing a model that coordinate recovery actions in the supply chain. Their basis is a robust schedule rather than a reactive schedule. Nonetheless, the study proposed in this paper aims to model a reactive schedule of a manufacturing industry that considers the information and decisions of customers industries, as conceptualised by Uhlmann et al. (2018), aiming to integrate their operational level.

2.3. Approaches and techniques

To choose the most suitable approach to integrate production rescheduling between industries, methods and techniques already used in the academic literature for rescheduling problems were consulted.

Raheja and Subramaniam (2002) and Ouelhadj and Petrovic (2009) listed some methods and techniques such as heuristics, meta-heuristics, knowledge-based systems, case-based reasoning (CBR), constraint-based scheduling, fuzzy logic, neural networks, hybrid techniques, and multi-agent systems (MAS).

Raheja and Subramaniam (2002) cited the Multi-agents in distributed artificial intelligence (DAI) as a method of schedule recovery that uses independent agents that work towards a goal. Ouelhadj and Petrovic (2009) evidenced that a multi-agent system is a promising area of current and future research in dynamic scheduling. For these authors, the design of multi-agent systems is motivated to reduce complexity, increase flexibility, and enhance fault tolerance. The agents interact by observing their environment, having the ability to communicate and cooperate to reach a global schedule derived from local schedules. Thus, a multi-agent system was considered to be the most proper technique to solve the rescheduling problem of this research. That is because the rescheduling process will be dealt with in several agents (manufacturer and customers) that have to work cooperatively to reach the best global performance.

A literature review with the same criteria used in Section 2.1, adding the variations of keyword 'flow shop' in the Boolean logic, was addressed to identify methodologies that specially dealt with flow shop rescheduling.

The papers with proposed solutions for production rescheduling in flow shops did not use multi-agent systems approaches (Akturk and Gorgulu 1999; Yin et al. 2011; Valledor et al. 2018 and Uzun Araz, Eski, and Araz 2019).

According to Raheja and Subramaniam (2002), any repair strategy will cause a deviation from the initially optimised schedule. Therefore, the performance will not be optimal after rescheduling. Therefore, a better

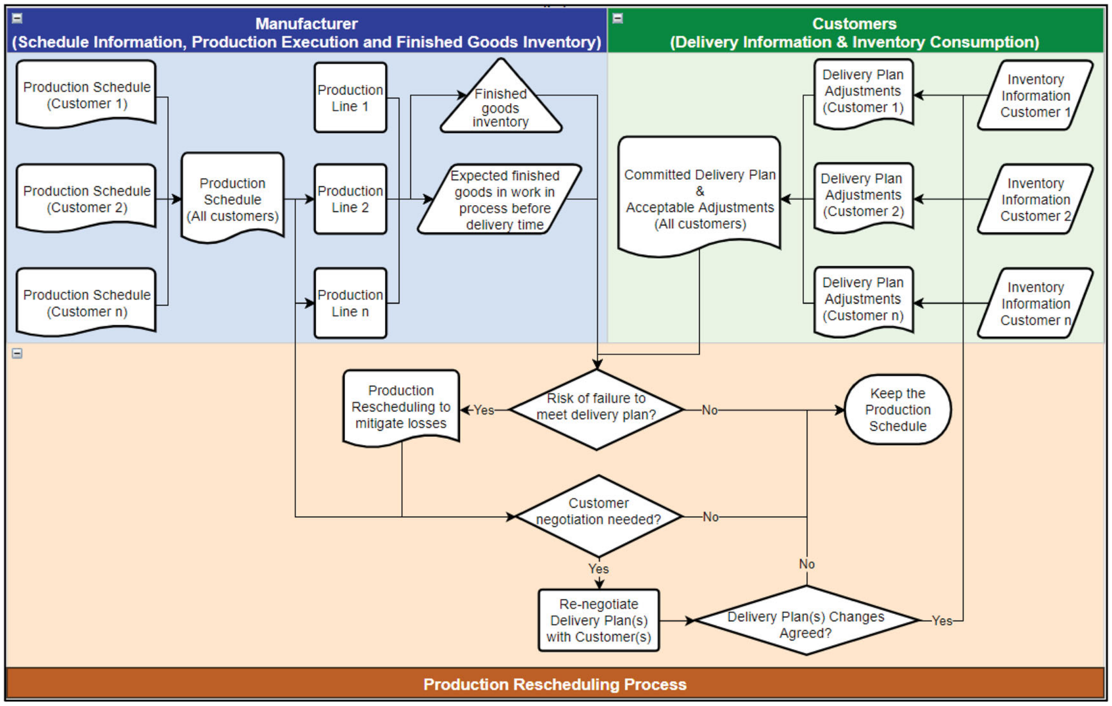


Figure 1. Conceptual model, adapted from Uhlmann et al. (2018).

schedule recovery strategy should lead to a minimum deviation of the performance measures. The main goal of the proposed model in this research is to meet customer satisfaction maintaining on-time delivery orders with the maximum committed quantity, focusing on reaching the best performance for factories and customers.

Based on insights from previous literature reviews and other studies related to solutions for flow shop rescheduling problems, a multi-method modelling will be used to handle a unidirectional HFS rescheduling, integrating a contract manufacturer (CM) and its customers.

3. Conceptual model

Based on Vieira, Herrmann, and Lin (2003); Pfeiffer, Kádár, and Monostori (2007); Kuster, Jannach, and Friedrich (2010) and Zakaria and Petrovic (2012), this research will address production rescheduling problems with reactive strategy, based on a previous initial predictive schedule, and a hybrid policy.

This research is an extension of an earlier work (Uhlmann et al. 2018), where a conceptual model of production rescheduling based on the evaluation of delivery risks to customers integrating two industries was proposed. The original model did not consider finished goods inventory to evaluate risks of not coping with delivery plans. Neither did it consider the need to execute a production rescheduling to mitigate the loss of shipment when customers do not agree to update their delivery plans. Figure 1 shows the updated conceptual model in the Manufacturer and the Production Rescheduling Process blocks. The main changes are explained as follows:

- Manufacturer (blue block), representing the factory. In this block a new ‘finished goods inventory’ box was added: Not only should the production execution monitoring be consulted, but also the finished goods inventory to check if there is any risk of failure to meet the delivery plans;
- Production Rescheduling Process (orange block), which shows the new rescheduling process integrating both industries. If ‘yes’ is the answer to the decision box ‘Risk of failure to meet the delivery plan?’: (1) the production rescheduling must be executed in order to mitigate the loss of shipment and (2) check again if there is still an issue to constrain the delivery accomplishment. Even if a customer does not agree to decrease the delivery quantity, the production rescheduling will be executed in order to mitigate the loss of shipment.

As informed previously, this research will follow a hybrid policy. The production rescheduling process (orange block) of the conceptual model (Figure 1) will be driven at any time in case of production disruption (event-driven). However, after the delivery shipment that occurs at the end-of-day, the active-schedule will be updated

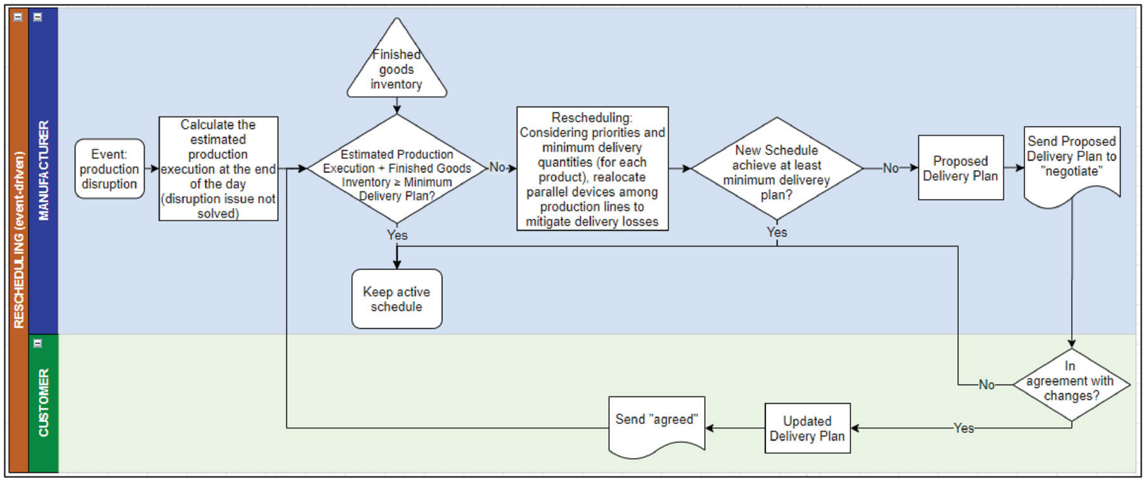


Figure 2. Event-driven rescheduling process.

(periodic). The following sections describe in more detail the rescheduling processes cited above.

3.1. Event-driven rescheduling process (triggered by production disruption)

Figure 2 explains the integration of the Event-driven Rescheduling Process in detail. Every time that disruption affects the production process, the manufacturer checks if the sum of the estimated production execution for the end-of-day and the finished goods inventory is enough to reach the minimum delivery commitment. In case the sum is enough to cover the minimum demand, the rescheduling process will not be activated. Otherwise, the rescheduling will be launched, acknowledging priorities and minimum quantities required by the customers. In this model, the bottleneck workstation is comprised of identical parallel devices that are used to reconfigure the production capacity in case of production rescheduling execution.

Moreover, the new schedule is activated immediately after the execution of the rescheduling process. The manufacturer will then, once more, check if the sum of the estimated production execution for the end-of-day and finished goods inventory is enough to reach the minimum delivery commitment. If it is sufficient, no customer negotiation is needed, else, a new delivery plan is proposed to the customer.

If a new delivery plan is proposed, the customer will then analyse it and decide on the accordance. If there is no agreement, schedule will be kept. Notwithstanding, the manufacturer will assume penalties due to incomplete shipment. On the other hand, in case of an agreement, delivery plan will be replaced by the newly approved. The manufacturer will then recheck the minimum deliver conditions, creating a loop in the process.

3.2. Periodic rescheduling process (updated at the end of the day)

Figure 3 illustrates the periodic rescheduling process that is executed on a daily basis at the end-of-day, after receiving the updated delivery plan from the customer.

First, the manufacturer needs to audit if the to-be delivered quantity in the updated delivery plan sent by the customer is equal or greater than the amount in the previous delivery plan, as less volume is not considered to be a profitable business. In the case of divergence, the manufacturer will send a message to the customer asking him to recheck their delivery plan. On the other hand, if no divergence is found, the production orders that are already in process will be rescheduled, followed then by open orders that are classified according to the customer's priorities.

After executing the rescheduling process, the system will check if the production quantity for each model inside the frozen period was kept, because contractual agreements do not allow variation in this period. However, due to good-business sense, changes on the delivery priorities without modifications of products and committed quantities between this period will be analysed.

The manufacturer will then check if the delivery plan for the frozen period can be achieved. On the occasion that it is, the manufacturer releases the new schedule. However, if not, it sends a collaborative delivery plan for the customer to decide whether to accept it. In case of non-agreement, the old delivery plan is kept, and the previously calculated schedule is released. It is important to highlight that actions out of the scope of this research should be taken to avoid penalties from customer, such as overtime. Notwithstanding, if there is an agreement, the delivery plan is updated and manufacturer rechecks the frozen-period volume condition, keeping the process in a loop.

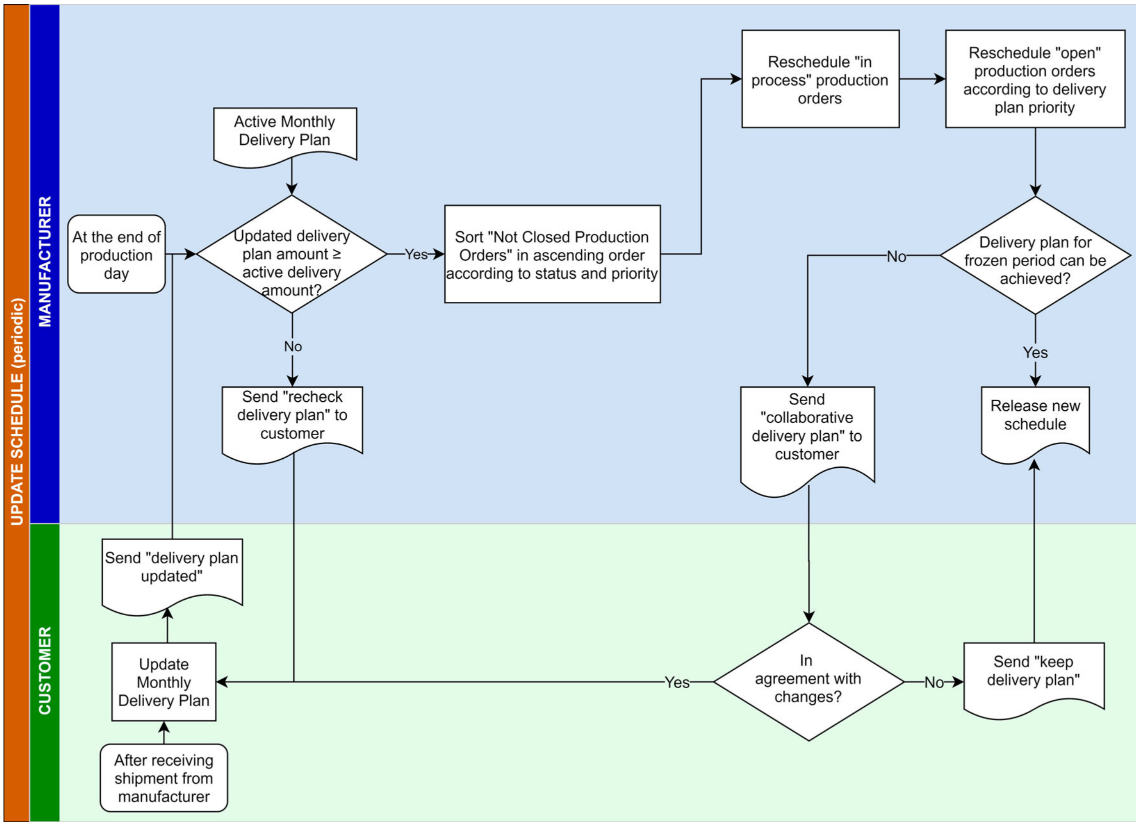


Figure 3. Periodic rescheduling process.

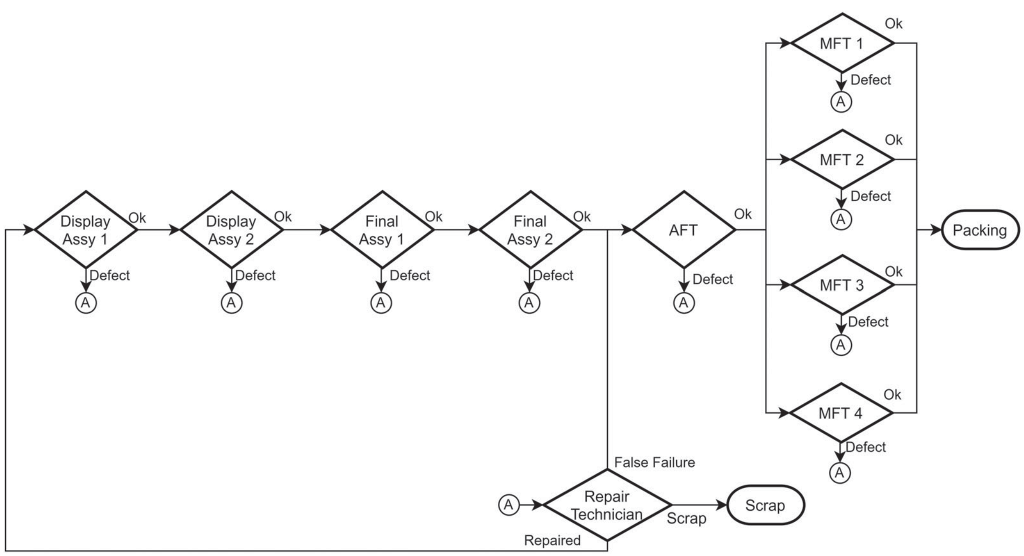


Figure 4. Car audio production process flowchart, adapted from Uhlmann et al. (2018).

4. Implementation

A unidirectional HFS was modelled using a multi-method combining discrete event and agent-based approaches to handle the rescheduling problem raised in this research. The modelling was performed using Any-Logic software, University Edition, version 8.4.0.x86_64.

4.1. Manufacturing system description

The CM factory (manufacturer) was structured as an unidirectional HFS system considers three 'final' lines that have the same configuration and capacity, being able to manufacture several car audio products, representing a FMS. Figure 4 illustrates manufacturing system adapted from Uhlmann et al. (2018); the Manual Functional Test (MFT) was split in four parallel and identical MFT devices, which can be reconfigured, by lending or borrowing devices, to adjust the production capacity, representing a RMS. The new configuration is: four assembly stations, an Automated Functional Test (AFT), four MFT devices and one packing station; if any operator detects any non-conformity, the product goes to a repair technician.

4.2. Multi-method modelling and simulation

In this topic the multi-method modelling, which involves the simulation of cooperative interactions among agents to handle rescheduling problems, is presented. The main agent used discrete-events to model the shop floor with three identical lines, along with the maintenance station, work in process (WIP), finished goods inventory. Some agents were designed only to record the characteristics of some elements, which are production order, work in process, and finished goods inventory. Nonetheless, the more important agents, in charge of cooperation to take decisions are reconfigurable device, rescheduling and customer. The model in AnyLogic software is described in this section and the communication among agents is explained in next section.

4.2.1. Main agent

The manufacturing system represented in this model consists of four sub-systems:

- Shop floor: It consists of three lines with their workstations that are represented by discrete elements, which are controlled by databases. The schedule is the main database, which is responsible for driving the sequence of production orders release;
- Maintenance station: When a breakdown on a MFT device occurs, it will be repaired in this workstation. There are two resources available to execute maintenance, in other words, two devices can be repaired at the same time. Moreover, they have flexible break times (lunches, etc.), so they do not follow the production schedule and maintenance execution is prioritised. Also, repair time follows a triangular distribution, being the MFT device downtime parameter;
- Work in process (WIP): At every full hour, the finished goods in the WIP inventory are moved to the finished goods inventory;
- Finished goods inventory: At the end of the business day, the finished goods stored in this inventory are shipped to the customer, limited by the maximum quantity requested in the delivery plan.

The customers' factories themselves were not modelled. Instead, four sets of buttons were created in the main agent to send customer's messages to the rescheduling agent, as follows:

- 'Proposed delivery plan' buttons: One of the buttons 'keep delivery plan' sends the message 'proposed delivery plan not accepted' for the factory. The other, 'delivery plan updated' sends the message 'proposed delivery plan accepted';
- 'Updated end of day delivery plan' button: To send the 'end of day updated delivery plan' message;
- 'Remade delivery plan' button: To send the 'end of day updated delivery plan' message;
- 'Collaborative delivery plan' buttons: One of the buttons 'update not accepted' sends the 'collaborative delivery plan not accepted' message and the other button 'update accepted' sends the 'collaborative delivery plan accepted' message.

4.2.2. Production order agent

This agent contains the characteristics of the production orders: production line, product name, quantity, and priority. These parameters are useful to link the information of the production order with their correspondent order agent.

4.2.3. Reconfigurable device agents

These agents represent each device used in the MFT workstation of each production line. They are linked to the resource pool, which controls the use of each one of these agents.

4.2.4. Work in process agents

Each agent of this type contains the characteristics of the finished goods in WIP: production line and product name. This is useful to calculate the estimated end-of-day production execution, which will be added to the finished goods inventory to check if the achievement of the minimum delivery commitment is feasible.

4.2.5. Finished goods inventory agents

Each agent of this type keeps the same characteristics of a work in process agent.

4.2.6. Rescheduling agent

This agent is in charge of the rescheduling process; its state chart is shown in Figure 5. The 'active' state (green box) starts when the initial schedule that is provided by the CM factory is released in the first production second. Once activated, this agent can follow two different paths: (1) event-driven rescheduling (yellow boxes) or (2) periodic rescheduling (blue boxes).

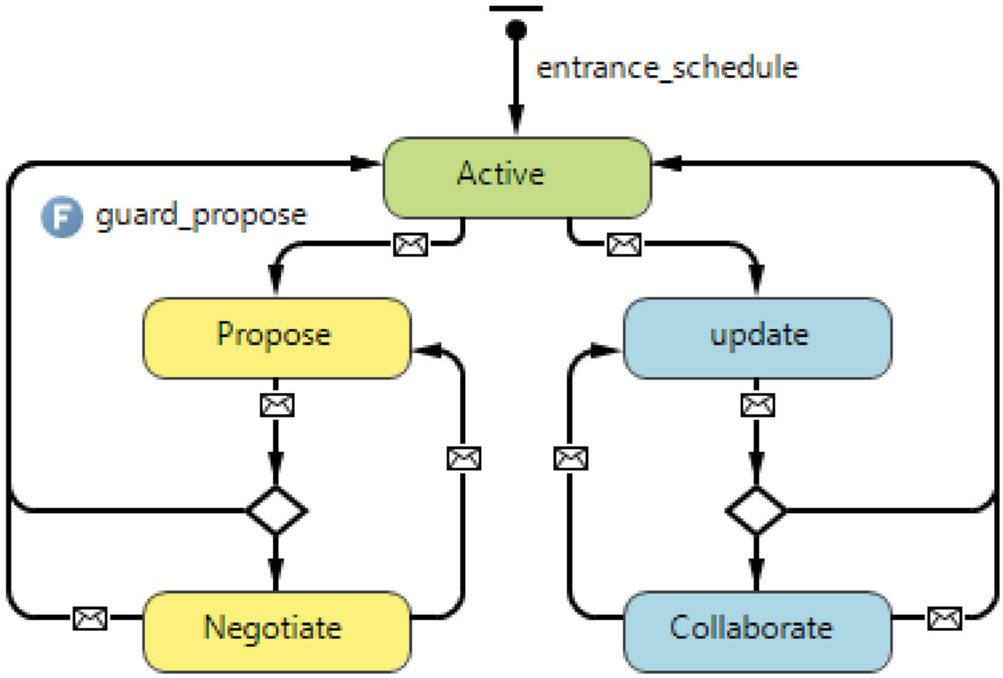


Figure 5. AnyLogic statechart of the rescheduling agent.

- Event-driven rescheduling: The transition to the 'Propose' state will occur every time that one or more MFT devices fail and the sum of the estimated end-of-day production execution and the finished goods inventory is not enough to reach the minimum delivery commitment. The production of the failed devices is not considered in this calculation. In this state, a reactive schedule is executed considering the minimum delivery plan as a target. The code will try to lend MFT devices from processes that are in a favourable situation to critical operations that contribute to the failure in meeting the delivery plan. If a new reactive schedule can reach the minimum delivery plan, the agent will return to its 'Active' state. Else, the agent will go to its 'Negotiate' state. In this state, a 'negotiate' message and a proposed delivery plan will be sent to the customer agent. After an analysis of the proposal, the customer can either accept or reject the negotiation. The first will return the message 'Proposed delivery plan accepted', which will once more trigger the 'Propose' state of the rescheduling agent. On the other hand, the second will return the message 'Proposed delivery plan not accepted', which will cause the rescheduling agent to return to its 'active state'. Hence, the CM factory will assume penalties due to incomplete shipment.
- Periodic rescheduling: At the end of each production day, every business day, after receiving the 'updated delivery plan' message from the customer, the agent will assume its 'Update' state. In this state, the code will check if the quantities of the new delivery plan are equal or greater than of the original plan. In case of divergence, the agent will assume its 'collaborate state', sending the message 'remake delivery plan' to the customer. After the customer has reviewed the delivery plan to align it according to the to the contractual terms, it will send a 'updated delivery plan' message to the rescheduling agent, who will return to its 'update state'. The code will, again, perform the initial checks. If the delivery plans are aligned, the rescheduling will be executed, prioritising the production orders that are already in execution, followed by the 'open' orders that are classified according to the customer's priorities. After reallocating all not 'closed' orders, the feasibility of the delivery plan commitment inside the frozen period will be checked. Hence, modifications on delivery priorities without changes of products and quantities will be analysed, even if this situation is not allowed in contractual agreements. If it is feasible to complete the delivery plan inside the frozen period, the new schedule will be released and the agent will go to its 'active' state. However, in case of non-feasibility, the agent will change to its 'collaborate' state and send a collaborative delivery plan to the customer. The customer should then decide to accept or reject the collaborative delivery plan. If accepted, it will return an 'updated delivery plan' message to the rescheduling agent. It will then change its state back to its 'update' and will follow the flow of events. On the other hand, if rejected, a 'keep delivery plan' message will be sent to the rescheduling agent. In this case, this agent will assume its 'active' state and release a new

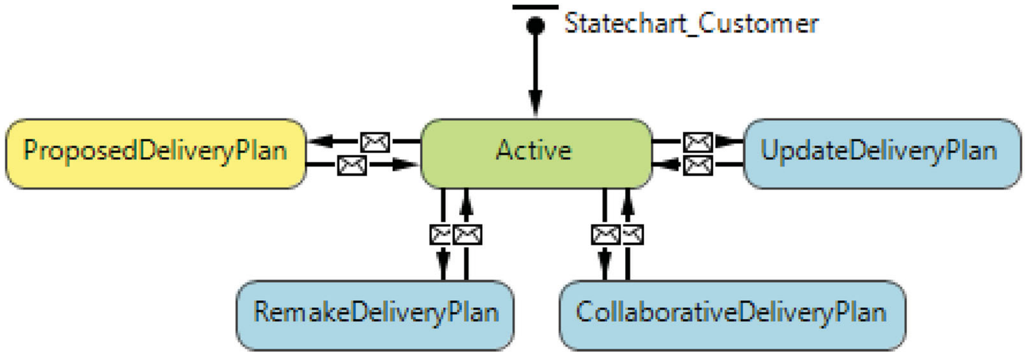


Figure 6. AnyLogic statechart of customer agent.

schedule. Thus, the CM Factory will assume penalties due to incomplete shipment.

4.2.7. Customer agent

This agent is in charge of making delivery plan adjustments. The state chart of the customer agent is shown in Figure 6. The 'active' state (green box) is released in the beginning of the simulation. Once activated, this agent can follow four different paths: the box in yellow shows reaction during the event-driven rescheduling and the boxes in blue show reaction during the periodic rescheduling.

- Proposed Delivery Plan: This state is activated when a 'negotiate' message is received from the rescheduling agent. In this state, the customer will analyse the proposed delivery plan sent by the factory, which can be either accepted by sending 'proposed delivery plan accepted' message to rescheduling agent, or rejected by sending 'proposed delivery plan not accepted' message to rescheduling agent. In both cases, after the analysis of the delivery plan, the customer agent will return to its 'active' state;
- Update Delivery Plan: This state is activated at end-of-day when the customer receives the daily delivery shipment from the factory. After analysis, a new delivery plan and an 'end of day updated delivery plan' message are sent to the rescheduling agent. After that, the customer agent returns to its 'active' state;
- Remake Delivery Plan: This state is activated when a 'remake delivery plan' message is received from the rescheduling agent. In this state, customer will review the delivery plan focusing on aligning it according to the contractual terms. Then, a new delivery plan and an 'end of day updated delivery plan' message are sent to the rescheduling agent. Thus, the customer agent returns to its 'active state;
- Collaborative Delivery Plan: This state is activated when a 'collaborate' message is received from the rescheduling agent. In this state, the customer will analyse the collaborative delivery plan proposed by the factory, which can be either accepted by sending 'collaborative delivery plan accepted' message to rescheduling agent, or rejected by sending 'collaborative delivery plan not accepted' message to rescheduling agent. In both cases, after the delivery plan analysis, the customer agent will return to its 'active' state.

As informed previously, the customer's factory is not modelled in this simulation. Buttons located in the main agent are used to create the communication between customer and factory.

4.3. Communication among agents

The already-described rescheduling processes are illustrated utilising two Unified Modelling Language (UML) diagrams, which are presented in Figure 7, event-driven, and Figure 8, periodic-event.

4.4. Scenarios and data applied in the simulation model

Three scenarios were used to test the model proposed in this research:

- Scenario 01: scenario with cautious downtime parameters (based on real case), to verify the usual factory performance without customer integration (adjustments are not allowed in the committed delivery plan);
- Scenario 02: scenario with challenging downtime parameters, to verify the factory performance without customer integration (adjustments are not allowed in the committed delivery plan);
- Scenario 03: scenario with challenging downtime parameters, to verify the factory performance with customer integration, considering a flexible delivery plan with adjustable minimum and maximum quantities.

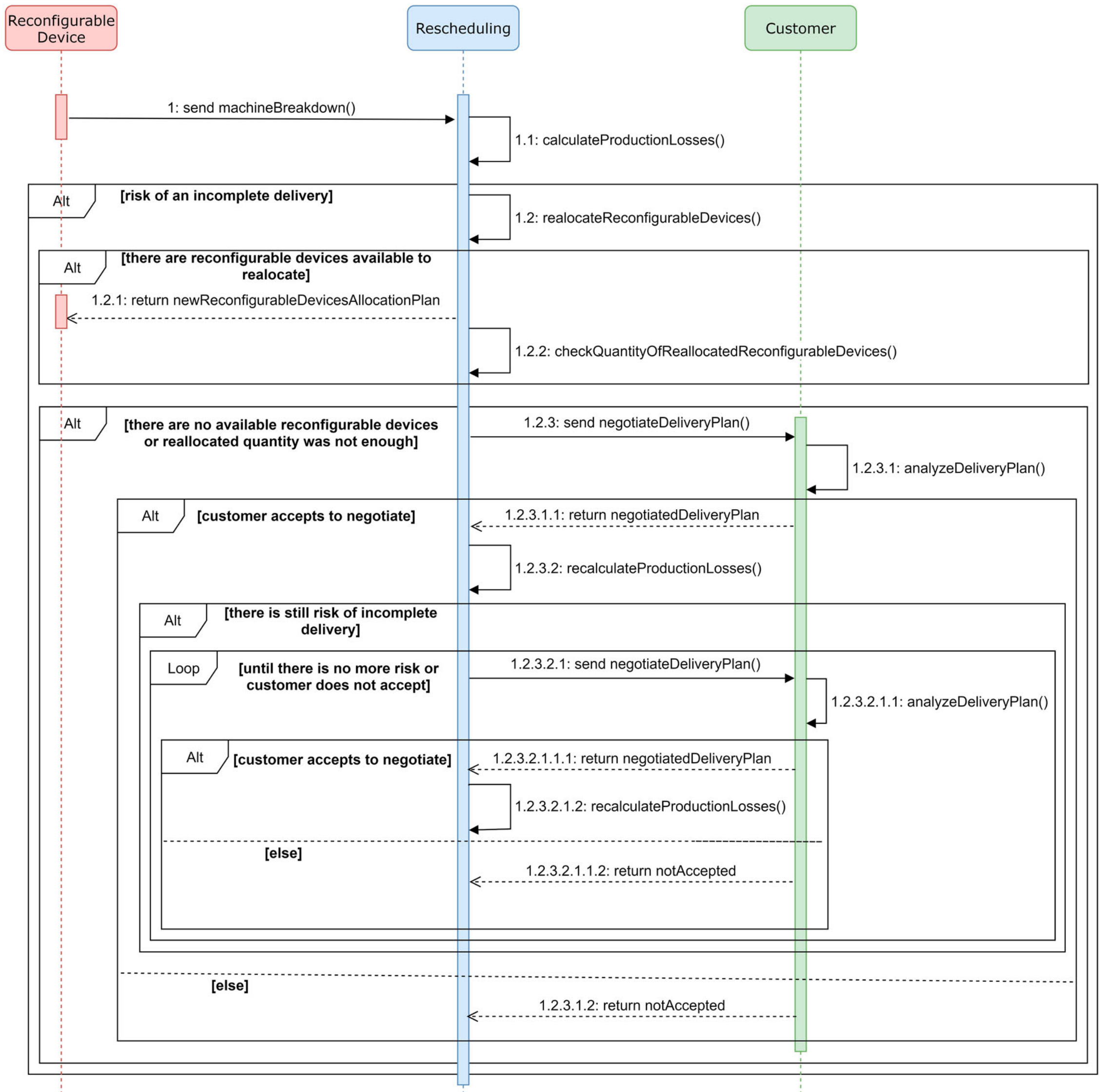


Figure 7. UML sequence diagram of the data exchange among agents (event-driven).

The data used in this test case are reported as follows:

- Disruption event (MFT device breakdown) for scenario 01: Poisson (7.2) days;
- Disruption event (MFT device breakdown) for scenarios 02 and 03: Poisson (3.6) days;
- Downtime (time to repair devices) for scenario 01: Triangular (6, 120, 20) minutes;
- Downtime (time to repair devices) for scenarios 02 e 03: Triangular (9, 180, 30) minutes;
- Simulation calendar: From Jan/02nd to Jan/31st;
- Production time: Monday to Thursday, 07:05am to 05:15pm; Friday, 07:05am to 03:15pm;
- Break times: 09:00am to 09:15am; 03:00to 03:15pm;
- Lunch time: 12:00am to 01:00pm;
- Backflush cycle time: 60 min, moving products to finished goods inventory;
- Delivery time: Monday to Thursday, 4:00pm; Friday, 2:00pm;
- Initial production schedule: Real data;
- Initial delivery plan: Based on initial production schedule (starting on next day after production day);
- Setup: Real data: 10 min;
- Run rate & Cycle times: Real data, 85% full capacity;
- Technical repair: 30 min;
- First Pass Yield (FPY): Real data, 98.80%;
- Failure Rate: Real data, True Failure 1.18%; False Failure 0.02%;
- Scrap: Real data: 0.33%.

To simplify the simulation model some assumptions were established:

- Customers operation is not to be considered in this simulation model;

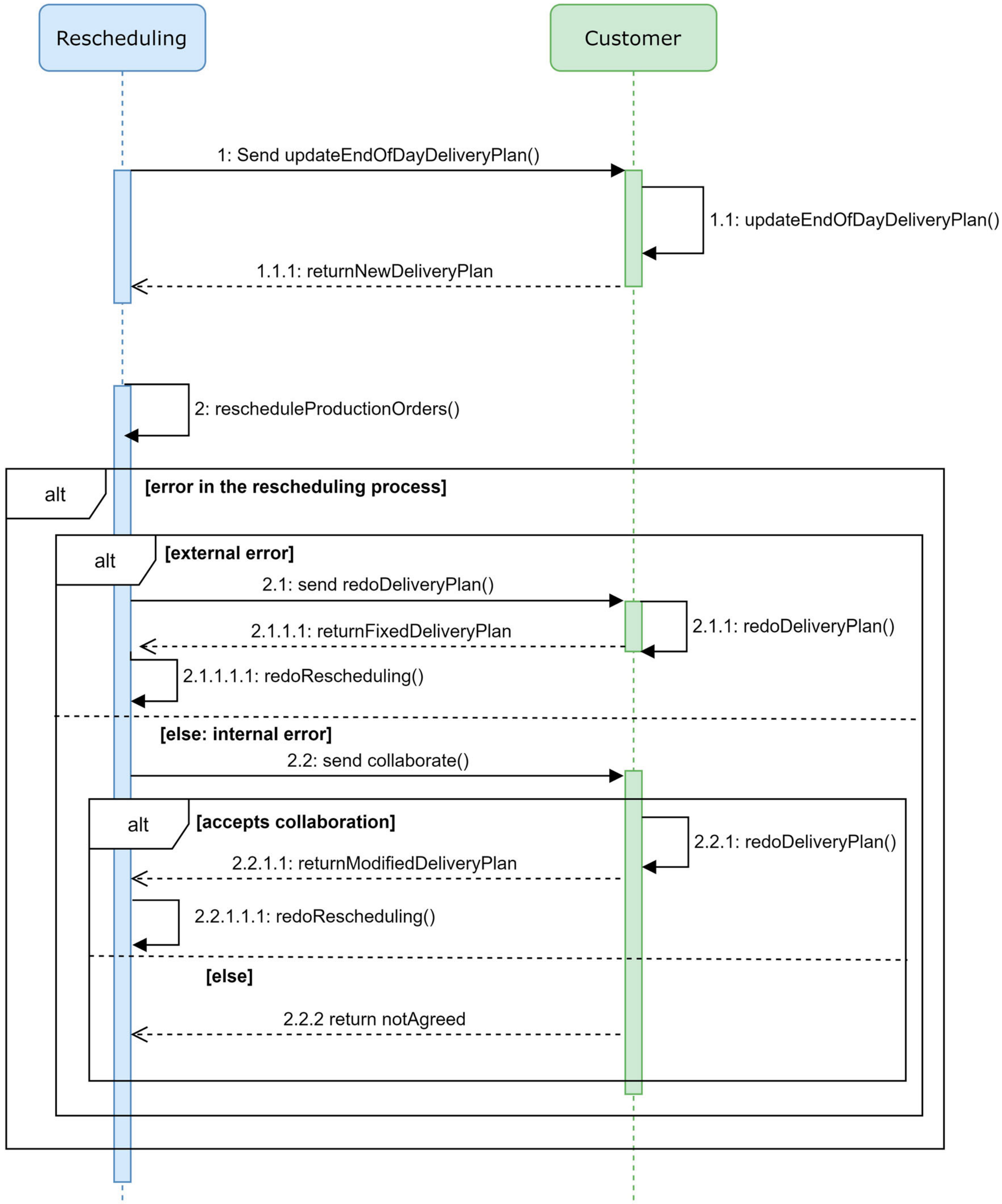


Figure 8. UML sequence diagram of the data exchange among agents (periodic).

- Initial schedule is provided by the planner;
- There are no raw material constraints;
- Preventive maintenance times are not considered;
- Increases in volume of initial delivery quantities are not considered;
- Minimum Order Quantities (MOQ) and Order Increment (OI) quantities are not considered in the Delivery Plan;
- Production is executed according to the schedule, and everything that is produced until 3:00 pm (2:00 pm on Friday) is moved to the finished goods inventory. Products manufactured after this time will not be considered as available inventory for shipment at the same day.

4.5. Empirical logic to adjust flexible delivery plan

Every time that disruption affects the production process, the manufacturer checks if there is any risk of delivery loss. A proposed delivery plan will be sent to the customer when the sum of the estimated production execution of the end of the day, without taking account the failed

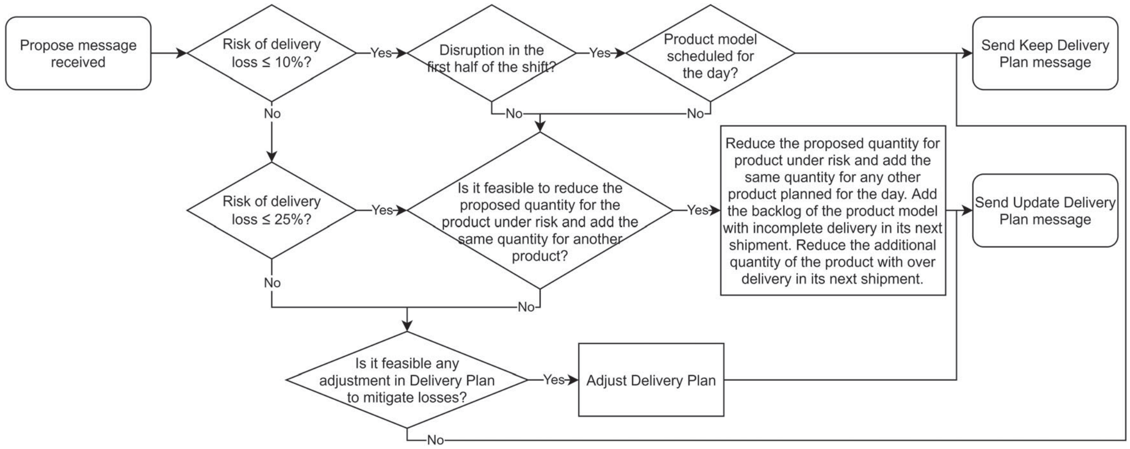


Figure 9. Empirical logic to adjust the flexible delivery plan.

devices, and the finished goods inventory is not enough to reach the minimum delivery commitment.

In this simulation model, the operation of the customer is not designed. Therefore, it is not possible to take decisions to adjust the delivery plan based on the customer's production execution. Due to this fact, to establish a logical sequence to be followed during the customer's analysis of the proposed delivery plans, Figure 9 presents an empirical logic to adjust minimums and maximums quantities of the committed plan.

When customers receive a 'proposed' message, they check the reduction percentage of the minimum delivery in the proposal, in comparison with the minimum delivery in the active plan. Then they can decide between two options:

Keep delivery plan in case:

- The risk of delivery loss is less or equal to 10% for disruption in the first half of the shift, and production orders for the product model scheduled for the analysed day exist;
- The risk of delivery loss is over 25%, and there is not any available adjustment to mitigate losses.
- Update delivery plan in case:
- The risk of delivery loss is less or equal to 10%, and the disruption is happening in the second half of the shift, but it is feasible to reduce the proposed quantity for the product under risk, adding the same amount for another product;
- The risk of delivery loss is less or equal to 10%, the disruption is happening in the first half of the shift, and there is a lack of production orders for the product model in the analysed day, but it is feasible to reduce the proposed quantity for the product under risk, adding the same amount for another product;
- The risk of delivery loss is more than 10% and less than 25%, but it is feasible to reduce the proposed quantity for the product under uncertainty by adding the same amount to another product;
- The risk of delivery loss is over 25%, but some adjustments are feasible to mitigate losses.

When it is feasible to reduce the proposed quantity for the product under risk, adding the same amount for another product, the instruction is:

(1) Reduce the proposed quantity for product under risk;
(2) Add the same quantity for any other product planned for the day;
(3) Add the backlog of the product model with incomplete delivery in its next shipment;
(4) Reduce the additional quantity of the product with over delivery in its next shipment.

4.6. Results and analysis

This section presents the results of the simulation based on the previously informed scenarios. The simulation of each production day takes around 30 s. However, the execution stops due to any interruption at MFT station (event-driven rescheduling) and at the end of each day (periodic rescheduling). This is because it is necessary to wait for the customer decisions. Moreover, decisions are performed by pressing buttons, restarting the simulation.

Figure 10 illustrates the MFT devices' downtime for each scenario. Scenario 1 shows the cautious downtime of approximately 34 min, whereas Scenario 2 and 3 shows a challenging downtime, being over than 134 min.

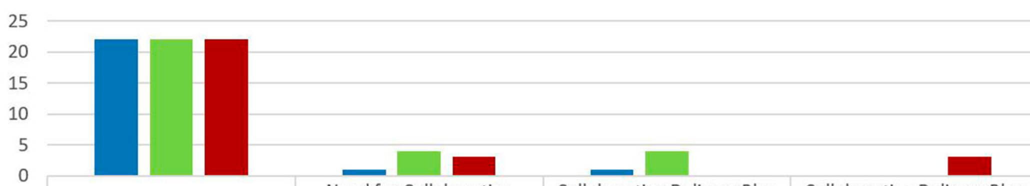
Scenario 1 is based on the real industrial situation, with low downtime parameters and without customer integration. The analysis is focused in Scenario 2 and 3 that display challenging downtime parameters, scenario 2 (without customer integration) and scenario 3 (with customer integration).

	Scenario 1	Scenario 2	Scenario 3
MFT Devices Line1	12:34:09	48:00:57	54:33:38
MFT Devices Line2	9:14:17	47:05:19	54:13:53
MFT Devices Line3	12:24:40	39:25:12	40:15:08

Figure 10. Downtime of MFT devices.

	Scenario 1	Scenario 2	Scenario 3
Initial Schedule	15395	15395	15395
Executed Production	15265	14247	14407
Balance	-130	-1148	-988
Performance	99,16%	92,54%	93,58%

Figure 11. Production performance (initial schedule × executed production × balance).



	Periodic Rescheduling (at the end of the day)	Need for Collaborative Delivery Plan (periodic rescheduling)	Collaborative Delivery Plan Not Accepted (periodic rescheduling)	Collaborative Delivery Plan Accepted (periodic rescheduling)
Scenario 1	22	1	1	
Scenario 2	22	4	4	
Scenario 3	22	3		3

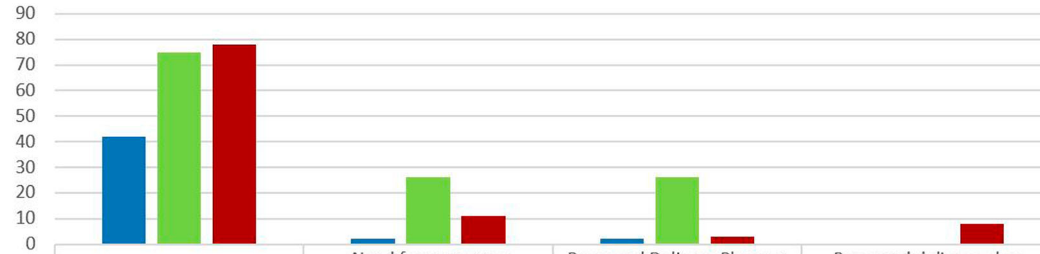
Figure 12. Quantity of periodic rescheduling and agents' decisions.

Figure 11 shows that the production execution of 93.58% in scenario 3 was slightly higher than the result of 92.54% in scenario 2. But, due the partnership environment, the need of rescheduling or negotiation between the industries were reduced in scenario 3:

(1) Figure 12 illustrates that the periodic rescheduling was triggered for the 22 workdays in both scenarios. Notwithstanding, scenario 2 shows the needed of one additional negotiation for a collaborative plan and;
(2) Figure 13 shows that almost the same quantity of MFT devices failed in both scenarios. Yet, customer negotiations were triggered only 11 times in scenario 3, in comparison with 26 times in scenario 2.

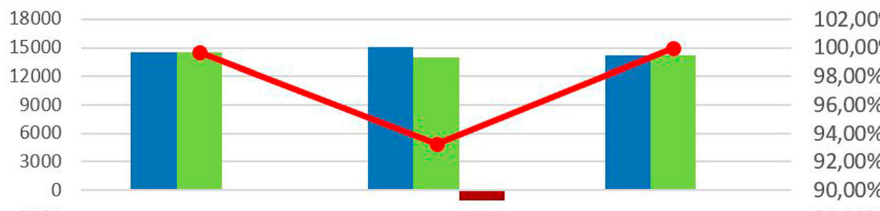
Figure 14 shows that although production downtime has increased, scenario 3 presents the best delivery performance (99.99%) and has missed only 2 units of the minimum volume committed. Additionally, Figure 15 illustrates only 10% of incomplete deliveries in the third scenario (four shipments delivered with less than the minimum committed quantity), in comparison with 21.1% in scenario 2.

The results show that the previous knowledge of allowed adjustments in delivery plans authorises fast



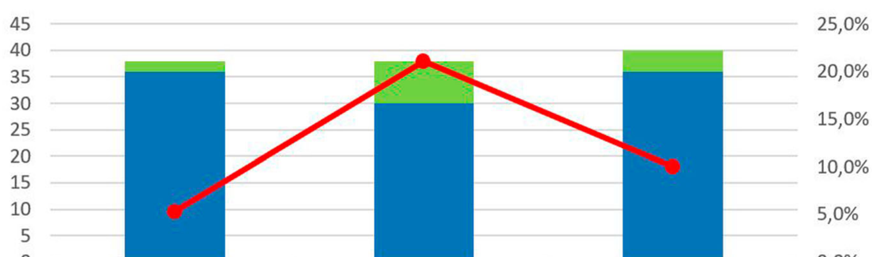
	Event-Driven Rescheduling (MFT device failed)	Need for customer negotiation (Event-Driven Rescheduling)	Proposed Delivery Plan not accepted (Event-Driven Rescheduling)	Proposed delivery plan accepted (Event-Driven Rescheduling)
Scenario 1	42	2	2	
Scenario 2	75	26	26	
Scenario 3	78	11	3	8

Figure 13. Quantity of event-driven rescheduling and agents' decisions.



	Scenario 1	Scenario 2	Scenario 3
Minimum Delivery Plan	14531	15028	14219
Delivered	14482	14013	14217
Delivery Balance	-49	-1015	-2
Performance	99,66%	93,25%	99,99%

Figure 14. Delivery performance (minimum delivery plan × executed delivery plan).



	Scenario 1	Scenario 2	Scenario 3
Incomplete	2	8	4
Complete	36	30	36
% Incomplete Delivery	5,3%	21,1%	10,0%

Figure 15. Status of deliveries (deliveries less than minimum committed).

reactions in the initial schedule. Also, the integration of information and decisions can avoid unnecessary attrition caused by a common disruption in the production line.

5. Conclusions

This paper presented a novel hybrid flow shop rescheduling procedure, addressing the integration of manufacturing services and industrial customers in dynamic contexts, using multi-method modelling. The model can perform production rescheduling at a manufacturing plant, consulting the available adjustments of the delivery plan from the customer side. The simulated results show that the proposed model does, in fact, improve production and delivery performance even with challenging production downtime indicators. As a limitation, customers' factories were not modelled and manual triggers were used to emulate the customer's messages. On the other hand, the messages from agents were based in an empirical logic derived from the authors' professional experience. Recommendations for future research embrace the consideration of customers' factories and suppliers' factories in the simulation model and the insertion of financial data to evaluate the impacts of contractual penalties caused by uncompleted deliveries. Finally, it is encouraged the design of a computational system able to integrate information of involved industries to execute this model in a real shop floor, which can be a practical application of this model using the research-action approach.

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