This is an Accepted Manuscript of an article published by Taylor & Francis in Enterprise Information Systems on 19 April 2023 available at: https://doi.org/10.1080/17517575.2023.2203430”

PREPRINT

A System Dynamics Approach to unlock the complexity of the S&OP in Virtual Enterprises

Rodrigo Furlan de Assis[1, 6], Luis Antonio de Santa-Eulalia[2], Fabiano Armellini[3], Rosley Anholon[4], Izabela Simon Rampasso[5], Fabio Müller Guerrini[6], Moacir Godinho Filho[6, 7], William de Paula Ferreira[1,*]

[1] Department of Systems Engineering, École de Technologie Supérieure, 1100 Notre Dame Street, West, Montreal, QC, H3C 1K3, Canada.
[2] Business School, Université de Sherbrooke, Sherbrooke, QC, J1K 2R1, Canada.
[3] Department of Mathematics and Industrial Engineering, Polytechnique Montreal, QC H3C 3A7, Canada.
[4] School of Mechanical Engineering, University of Campinas, Campinas, Brazil.
[5] Department of Industrial Engineering, Universidad Católica del Norte, Antofagasta, Chile.
[6] Department of Industrial Engineering, University of São Paulo, São Carlos, Brazil.
[7] EM Normandie Business School, Metis Lab, Le Havre, France.

ARTICLE HISTORY
Compiled April 26, 2023

ABSTRACT
Companies have explored different collaborative approaches in the search for better performance in a competitive and highly dynamic business environment. Among the typologies of existing collaborative networks, one of the most prominent is the Virtual Enterprise (VE). VE enables organisations to compete by strengthening their core competencies and sharing risks through collaboration. However, for manufacturing-based VE, the literature fails to provide adequate simulation-based methods for understanding the complex behaviour of the production planning step at the tactical level, known as Aggregate Production Planning or Sales & Operations Planning (S&OP). It refers to a decision-making process with several interacting variables that creates complex behaviours for production planners from different organisations who collaborate only in a sporadic moment. In this context, this paper proposes a novel System Dynamics-based model to help to understand the dynamic behaviour of S&OP in VE. To test and perform a preliminary model validation, a real-scale industrial proof-of-concept case was developed to help decision-makers study alternative production policies and create different planning scenarios to identify critical situations at the tactical planning level. Results suggest the efficiency of the proposed model, including its ability to straightforwardly make simulation-based S&OP scenarios comparisons, thus expanding the analytic decision-making capacity of managers desiring to push the limits of traditional S&OP in VE.

KEYWORDS
Virtual enterprises; Collaborative networks; Aggregate production planning; Sales & Operations Planning; System Dynamics; Simulation modelling.

*Corresponding authors: de Paula Ferreira, W. Email: william.ferreira@etsmtl.ca

1. Introduction

To allow companies to survive and prosper, diverse organisational network models have emerged in the last decades (Nayeri et al. 2021), allowing companies to cooperate and share competencies and resources (Iandoli et al. 2012). Among them, Virtual Enterprises (VE) is considered a powerful alliance model that creates a temporary and vertical structure formed by independent institutions, businesses or individuals that collaborate spontaneously and ephemerally to better respond to business opportunities (Trapp et al. 2021). A fundamental key competence for the joint operation of distributed companies is integration, i.e. taking into account the partners' skills, abilities, and availability (Pisching et al. 2015). Traditionally, there are several challenges to structuring VE, among which are the need to select partners, develop products, and operationalise activities among members (Durugbo 2016).

Thus, building a computational support system for a VE based on partner data/information modelling becomes a critical issue (Zhang and Li 1999). In addition, business integration for the VE, mainly integration planning, is a crucial element of VE operation and it requires considerable innovative efforts (Cheraghalikhani et al. 2019). More specifically, one of the essential elements to operationalise VE is the process of planning production and capacity utilisation levels for a medium-term horizon (tactical level). This means balancing production and demand to find the best fit of shared capacity among all partners, which is known as Aggregate Production Planning (APP) or, more recently, Sales & Operations Planning (S&OP) (Jamalnia et al. 2019; Thomé et al. 2012). However, APP-oriented approaches, like S&OP, stand for a complex business process with several interacting variables that can create many possible planning scenarios with complex behaviours (Jamalnia et al. 2019).

In this context, modelling and simulation methodologies can be used to formalise the S&OP and help understand its behaviour globally. Modelling and simulation are described through various approaches employed in the context of Industry 4.0, of which discrete-event simulation (DES), agent-based modelling and simulation (ABMS), and System Dynamics (SD) can be highlighted (de Paula Ferreira et al. 2020, 2022a, 2021, 2022b). SD is a strategic simulation modelling approach that uses differential equations and feedback diagrams to analyse dynamics in systems represented by high-level abstraction models (de Assis et al. 2021; Scheidegger et al. 2018). Furthermore, considering the aggregate nature of S&OP and its focus at the tactical level, an SD application may provide conditions to study the results of the interactions and interrelationships between its components (Jamalnia et al. 2019).

Related to the problems of operationalising partner selection for VE and planning resource allocation among members, this research aims to propose an SD model to better understand the dynamics of S&OP in VE (hereafter S&OP-VE). The main idea is to create a dynamic model to support decision-makers in establishing general guidelines for the creation of a new VE, especially concerning capacity and competence management to conduct shared business processes. This paper contributes to minimising the effect of inter-firm integration challenges by presenting a model that can handle the specific characteristics and attributes of VE members and provide information for distributed planning of production levels and capacity utilisation over a medium-term horizon (tactical level). To perform some preliminary tests, a real-scale industrial model is developed.

This paper is organised into five sections. After this introduction, Section 2 presents one of the essential elements to provide the conceptual background and a literature review. Section 3 presents the methodology. Section 4 the proposed SD model. Section

5 builds the proof-of-concept case results. Section 6 discusses the results obtained. Finally, Section 7 concludes the paper and suggests some future research.

2. Background and literature review

2.1. *Collaborative networks and VE*

Collaborative networks are defined as a network of organisations formed by a set of autonomous entities, distributed geographically, in which participants collaborate to achieve common goals. The interaction among participants is supported by the development of information and communication technologies (Camarinha-Matos et al. 2009). A collaborative network is related to five basic features: at least one collaborative purpose; at least one collaborative task; members with complementary characteristics; definition of a collaborative system of rules or governance processes; and the existence of legal norms for internal and external representation and organised structure (Baum and Schütze 2013).

Among the typologies of collaborative networks oriented towards a single project or business opportunity, Virtual Companies (VC) and VE stand out (Rojas et al. 2012). The concept of VE is primarily technologically driven and is based on the use of information systems. VE is a dynamic and temporary network collaboration among autonomous entities that interact to meet a specific opportunity, sharing skills, resources, risks and benefits (Crispim et al. 2015; Camarinha-Matos et al. 2009). On the other hand, VE shares resources and skills to accomplish its mission and objectives with a cooperation model that is not limited to an alliance of for-profit companies, often emerging from virtual organisations (Camarinha-Matos 2014).

Research on VE has emerged since the 1990s. Still, the term VE was first coined in the late 1980s regarding virtual (invisible) links between ICT-supported enterprises (Anthony Jnr and Abbas Petersen 2021). The earliest definition of VE may refer to Zhang et al. (1997) and Chu et al. (2002). In particular,Zhang et al. (1997) were the first to view a VE from a designer's perspective, which means that the topology of VE becomes a variable, and the concept of the structure of VE is also defined. Zhang and Wang (2016) propose applying the design theory and methodology available to design and construct a VE. Chu et al. (2002) were one of the earliest works to build a framework for one of the critical problems in creating a VE.

Due to its risk-sharing characteristics and, consequently, the cost reduction it offers to members, VE is an exciting choice for new businesses (Camarinha-Matos 2014). VE benefits allow companies to focus on their core competencies, procure world-class resources, establish more economic relationships with suppliers, provide more efficient operations crossing organisational boundaries and share research and development (Durugbo 2016; Vaez-Alaei et al. 2022). VE depends on the successful execution of the VE life cycle phases, the adequate definition of functions for all members involved, and proper management of the components used in its operation (Bremer et al. 2001; Camarinha-Matos and Afsarmanesh 2007). Therefore, the VE life cycle and its features need to be evaluated from a systemic perspective as part of the strategic foundation of the VE companies. The VE life cycle is closely related to the creation and extinction of relationships developed to achieve the business opportunity on which they are based.

The VE life cycle begins in the creation phase; initial configurations are established in the beginning of VE life cycle, such as partner selection, contract negotiation, and level of information sharing (Camarinha-Matos et al. 2009; Gasparotto and Guerrini

2013). The relationship between the creation and operation phases raises a high level of complexity for a VE, as one adopts the VE manufacturing model without identifying the key functional requirements for capability and productivity among the members (Carvalho et al. 2005; Tan et al. 2010). The evolution/reconfiguration phase is observed only when operational instabilities require changes in the general configuration (Camarinha-Matos and Afsarmanesh 2007). In the dissolution phase, the partnership is finished due to the completion of business opportunities or some impediment to companies working collaboratively. When new opportunities happen, new collaborative processes can be established. From a dissolution, collaborative chains with more stable objectives and without temporary ties can be formed, giving rise to the supply chain, industrial clusters, or even distributed manufacturing systems (Pires et al. 2001; Vernadat 2010).

The main advantage of a global VE is manufacturing agility. The main disadvantage of the VE concept is its low reliability, robustness, and resilience, as each entity in a network has its executive power and can take more care of its claim. So, it is not easy to form a reliable network. Other restrictions on a VE result arise from differences in culture and system among a group of companies (Yu et al. 2021). One of the challenges in operations management for a VE is information systems integration, also called enterprise application integration. To deal with this challenge, an effective data model and efforts that have been developed mainly related to global VE are needed (Yu et al. 2021; Zhang and Li 1999).

To successfully operate a VE, integration between companies hierarchically at three levels is necessary. First is integrating the physical system that carries out the communication between the physical components distributed in several associated companies through computer networks and communication protocols. On the other hand, application integration performs interoperability and information sharing between member companies, allowing access to shared data standards by distributed applications. At the last level, business integration occurs through the coordination of business processes and sharing of knowledge between functional entities distributed in several associated companies (Gou et al. 2003; Romero et al. 2009).

According to Romero et al. (2009), the resources associated with the VE value chain are as follows: Physical resources - such as equipment and resources; ICT resources: such as software and hardware; Human resources - involve the competencies of the participating companies; Knowledge resources: through lessons learned shared by VE members. It has been possible to identify some responsibilities and roles focused on the perspective of action within the VE linking chains of involved companies to achieve maximum value-added, as shown in Table 1. The VE concept has both strengths and weaknesses due to four essential principles in forming a VE company: (1) willingness to join, (2) mutual agreement between its members, (3) self-benefit orientation, and (4) expansion of the competitive base (Pego-Guerra et al. 2010).

2.2. *Sales & Operations Planning in VE*

For Xia and Li (2008), S&OP development activities for VE are highly complex, given the number of variables that planning must meet for the operation of participating companies. Therefore, the authors define a set of principles guiding VE, among which are highlighted:

- Distribute operations: companies may be in different parts of the world, so geographical distance should not limit material availability and production capacity

Table 1. Additional roles developed by VE members

Member(s)	Description	Ref.
VE coordinator or Broker	The VE Coordinator or broker is the agent that integrates the skills of the companies participating in the VE to respond to new market opportunities.	1
VE members or partners	They are the companies that make up the network. The VE members participate in the collaboration primarily with their core competencies and present themselves to third parties as a unified organisation	2
VE strategist	Internal agent responsible for identifying the necessary competencies within the virtual organisation. Its function can also be performed by the broker.	3
Guest expert	Member or not of VE, who specialises in matters related to the product/service and can contribute technical details.	4
Virtual company client	External VE agent that needs to manufacture/produce a product or provide a service, such that this need results in a collaborative business opportunity.	5
Skills manager	An internal agent that deals with the competencies of participating companies, considering their limitations, and may propose changes in the selection of companies that do not have satisfactory performance.	6
VC production team	Internal VE agent that provides information necessary for planning and is responsible for planning, releasing, and updating production orders.	7
VC production coordinator	An internal agent that leads and coordinates the execution of production orders and the resolution of conflicts and the management of contingency mechanisms.	7

Legend: VE - Virtual Enterprise; VC - Virtual Company; [1]Camarinha-Matos and Afsarmanesh (2007); [2]Pego-Guerra et al. (2010); [3]Gasparotto and Guerrini (2013); [4]Romero et al. (2009); [5]Camarinha-Matos and Afsarmanesh (2007); [6]Vallejos et al. (2007); [7]Goulart et al. (2000).

analysis.

- Dynamic: promote the expansion or reduction of VE operations without disturbing previously established processes.
- Interoperable: heterogeneous information environments can use different technologies and operate on different computing platforms, so companies must relate their technological infrastructure efficiently.
- Based on Cooperation: Manufacturing companies must cooperate fully with their suppliers, partners, and customers to supply materials and components to commercialise the final product, and so on. This cooperation must take place in an efficient and quick-response manner.
- Autonomous: Although several companies are organised cooperatively, each company must maintain its autonomy.

To carry out the S&OP for VE, it is necessary to design structures capable of coordinating the participating companies' processes and activities. However, challenges must be overcome. Among the most cited in the literature, the following stand out: synchronisation of operational activities, integration of productive processes of distributed companies, and management of members' capacity. It is possible to position the S&OP for VE at two levels: i) S&OP for the VE: this is concerned with the general coordination of the forming parts of the VE and the results obtained. It proposes the aggregated planning of the VE, establishing deadlines, production orders, list of materials, product structure, and the responsibilities of each participating company; ii) S&OP for Participating Companies: the aggregated planning must be disaggregated and inserted in the planning of each participating company efficiently so as not to extrapolate the capacity of each participant (Camarinha-Matos et al. 2009).

For Chalmeta and Grangel (2005), the planning mechanism for the VE must be able to make conditions available to decision-makers: - Understand in such a way that there is no demand behaviour for changes in the production process; - Optimise the use of available resources and technologies; - Allow control of the production flow in case of occurrences that disturb these orders to guarantee compliance with delivery deadlines; - Develop configurable mechanisms according to an enterprise structure. For Castro et al. (2012), in the execution of the S&OP in networks of companies with shared operations, some difficulties are pointed out, such as: - Variation in efficiency levels: due to the variability of demand, high flexibility in the development of the production process is necessary, which in many cases increases the costs of preparation and programming of the production steps, as well as increasing the amount of material in the process; - Management of inter and intra-organisational relationships: by managing information from different areas and/or companies, the S&OP is in a constant process of negotiation with different agents within the production process, where it is necessary to consider different interests so that the available resources are on hand to meet the planning.

The specific literature explicitly integrating S&OP in VE is limited. Ouzizi et al. (2006) addressed demand behaviour and capacity constraints. Georgiadis and Michaloudis (2012) explore the variation in the participants' ability to simulate the operating levels of participating companies over time. In Ding et al. (2009), a heuristic algorithm based on the judgment solution method was proposed to adjust the task processing time so that the research results reduced training costs in a Chinese VE training case. Huang et al. (2013) present a production scheduling model with global scheduling and local scheduling for VE, using a genetic algorithm based on the shortest total production time of a set of items.

However, to the best of our knowledge, the simulation modelling literature is limited in the S&OP-VE domain, failing to provide tactic decision-making models that allow generating scenarios capable of expanding the understanding of the capacity of VE members operating in an integrated manner. Recognising capacity constraints before VE formation maximises network operational results. Even though the literature provides some studies addressing planning and SD, such as the work of Bajomo et al. (2022) in the area of management of material procurement, this paper is the first contribution to the S&OP-VE field.

3. Methodology

The theoretical background for the methodological part of this study is the design science research (DSR) paradigm, which puts forward procedures for conceptualising, developing, testing, and validating artefacts, which includes tools, methods, and models such as the one for the S&OP-VE proposed herein. By constructing and evaluating artefacts, design science focuses on providing innovative or more efficient solutions for organisational problems (Hevner 2007; Marques et al. 2021). In the case of this paper, the artefact is the S&OP-VE model addressing the problem of organising the APP structure for VE, improving the understanding of the supply chain, capacity, and productive structure for selecting companies in a VE formation.

An overview of the research design of this study is presented in Fig. 1. The artefact design cycle starts with awareness of business needs/problems (See Fig. 1). Next, possible solutions are designed based on the knowledge base of the problem space, built on foundations (e.g. theories, frameworks, constructs, models, methods, instantiations) and methodologies (e.g. data analysis techniques, formalisms, measures, validation criteria). Then, the assessment and refinement processes are performed. In the case of our paper, this assessment and refinement were done through a proof-of-concept case using real industrial data. It is worth mentioning that the "refinement and reassessment process is typically described in future research directions" (Hevner 2007, p. 80).

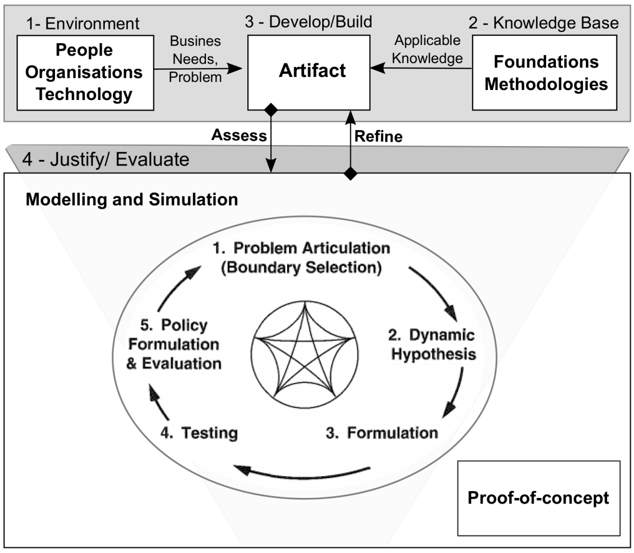


Figure 1. Research design
Source: adapted from Hevner et al. (2004) and Sterman (2000)

The artefact follows SD's methodological guidelines for modelling and simulation, which present relevant characteristics for developing efficient mechanisms to maximise decision-making capacity for collaborative networks (Assimakopoulos et al. 2006). When following the SD interactive steps (Problem Articulation, Dynamic Hypothesis, Formulation, Testing and Policy Formulation and Articulation - see the bottom part of Fig. 1), modellers develop relational and systemic interpretations of the relationships to which the variables defined in the object of study are submitted. This makes it possible to explore the interrelationship of these key variables, which are now controlled more rigorously to reduce the risk present in this type of system (Venkateswaran and Son 2007).

SD modelling and analysis are performed through control tools such as a feedback loop or stock and flow diagrams (de Assis et al. 2021; Scheidegger et al. 2018; Sterman 2010; Disney et al. 2004; Forrester 1997). The use of feedback loops implies a qualitative approach. In contrast, the use of stock and flow diagrams implies a quantitative approach (Kunc 2017), where the latter is the focus of this study for performing the computational experiments. The systems of SD present five basic components which are employed in this paper: state variables (stocks), control variables (flows or ratios), transformers (that can change the flows), connectors (that link system components), and feedback loops (that reinforce changes) (Morecroft 2015).

It is worth mentioning that SD, DES, and ABMS are the three most used modelling and simulation paradigms. SD deals with aggregated levels of modelling and is located at the highest level of abstraction, and DES is used in low to medium conception. As for ABMS, this technology is being used at all levels (Borshchev 2013; de Paula Ferreira et al. 2020). The S&OP-VE was developed using the SD methodology, as the application of SD to generate and analyse scenarios can be explored with good perspectives to broaden the understanding of the behaviour of managerial aspects for the structuring of manufacturing processes for the supply chain (Georgiadis and Michaloudis 2012; Schwaninger and Vrhovec 2006).

4. Proposed S&OP-VE Model

This section is focused on developing the modelling framework in SD for optimising the VE selection process. SD is a valuable instrument for complex planning structures, as it allows, through graphical representations and mathematical calculations, to develop of a relational interpretation of the different levels of interactive feedback to which the variables contained in the creation/operation are subjected to VE, for example. Furthermore, this simulation approach allows the members responsible for S&OP to explore the interrelationships and leverage points controlled with greater rigour to reduce the risks present in distributed production systems (Suryani et al. 2010). The S&OP-VE modelling was carried out through stock and flow diagrams, segmented into the following subsystems: supply management, production management, and capacity management, as described below and depicted in Fig. 2:

- Supply management: it provides raw materials based on demand according to the production order. Generally, production can only start with sufficient raw materials, which must be ordered appropriately to maintain the stock of parts or raw materials at adequate levels.
- Production management aims to transform production orders into intermediate and final products. There are two loops to control the two main stock types (work-in-process and final products), in which stock units are treated and accumulated as final products to be delivered in a pre-established time.
- Capacity management: in this process, the existing capacity restrictions are assessed to adjust production. This process can improve usage plans for the capacity according to the operational characteristics of the partners.

These subsystems directly influence the determination of production, inventory, capacity, and workforce levels, considering all details of the production planning for the tactical level, using probabilistic and deterministic variables for a selected planning horizon. This model is depicted in Fig. 2 using an instance with two partners, Enterprise A and Enterprise B. By developing the S&OP-VE model in a modular way, connecting different subsystems that can work together or separately, it becomes possible to bring greater flexibility for the construction of distributed plans, enabling the development of a knowledge structure about the typical operating characteristics of a VE. Thus, this model allows expanding the conditions for elaborating specific plans for each partner of the VE from the combination of these subsystems for as many network participants as necessary, establishing different levels of operation.

In addition to these modules, the $DemandManagement$ subsystem is also used. It is established as the entry point for demand values, which are exogenous to the model, following the premise that the model user provides these values. It is defined by the auxiliary variable *Demand*. Since VE is based on specific business opportunities, demand is usually based on specific customer contracts. Users can also model demand forecasting as constantly searching for new business opportunities. In this case, to generate initial demand values in the model, any distribution curve can be adapted to create new random numbers based on the characteristics of the forecasted demand.

The subsystem called $SupplyManagement$ in Fig. 2 shows how the supply struc-

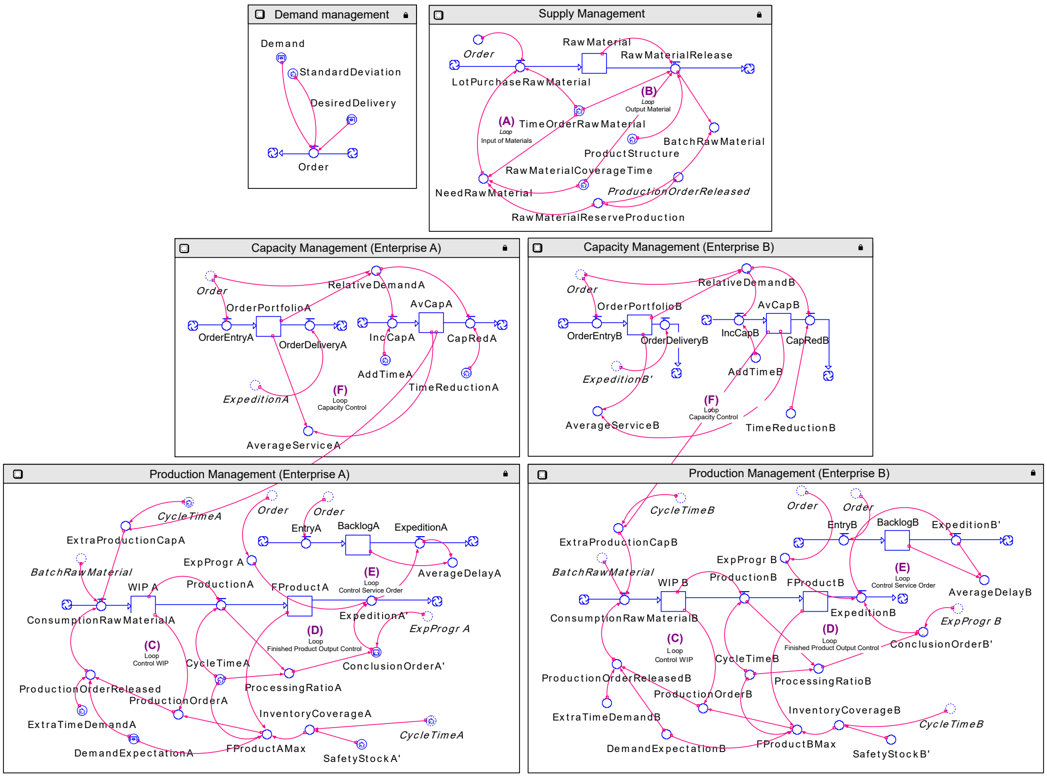


Figure 2. S&OP - VE (A and B) as an instance.

ture can include raw materials and components necessary to start production, according to the distribution curve proposed for the *Order* component. In this way, *Supplymanagement* is modelled as a feedback link structure that occurs using two fundamental loops for the behaviour of the proposed model (Loop Input of Materials (A) and Loop Output of Materials (B)). These loops make it possible to establish the link between the components used, and the operation of this subsystem only begins if there is a sufficient stock of materials to be consumed. For the Loop Input of Materials (A), the idea is to establish enough material stock levels until all demand is met. The second point occurs through the Loop Output of Materials (B), which shows that a certain amount of material is released for production.

The *ProductionManagement* subsystem allows production decisions for periods defined by the model operator. Like the one proposed for the *SupplyManagement* subsystem, the *ProductionManagement* subsystem also uses the relationship between loops to form feedback for the model operation. The main loops are the following:

- Loop WIP Control (C): Focuses on Work in Process (WIP), regulating initial production levels and establishing the relationship with the *SupplyManagement* subsystem, maintaining a production cycle for the expected time.
- Loop Finished Product Output Control (D): After finalising the production, a stock of finished products is generated. The delivery ratio consumes this stock. In addition, it is possible to define stock policies for finished products according to simulation needs.
- Loop Service Order Control (E): After order conclusion, products are dispatched to customer delivery, establishing delivery levels used by the model and targets

empirically defined.

The *ProductionManagement* subsystem aims to ensure production operation to meet the expected demand. For this, Loop WIP Control (C) uses a component called Work In Process (WIP) that regulates the production rate variation concerning the input of material for production. Loop Finished Product Output Control (D) establishes that, after the production process's completion, orders are accumulated for later delivery according to new delivery needs related to the demand value within the established time. Thus, the *Product* component establishes the index for final production, which calculates the average production volume of a process for a unit of time that the enterprise can achieve, given its current production level and production cycle time. Loop Service Order Control (E) considers the possibility of not meeting customers' orders due to production capacity variations. Therefore, it is possible to have a non-linear relationship between production and desired delivery level. This loop represents Backlog stock concerning order entry and order completion.

The *ManagementCapacity* subsystem was developed based on Elmasry et al. (2012). Elmasry et al. (2012) and Špicar (2014), as a complement to the application of the *ProductionManagement* subsystem, in which information related to the actual capacity of a participating member contributes or impairs production process behaviour. The capacity control structure accommodates and manages the flow related to open orders for each VE partner. The order portfolio formation results from the delivery time obtained in Loop (E) Service Order Control. During this period, there is an accumulation of open orders, information used to determine the order entry rate. Through Loop (F) Capacity Control, it is possible to establish the necessary capacity to meet the real demand.

4.1. *Main equations for S&OP-VE*

For *DemandManagement*, distribution is defined by the *Order* component according to Eq. 1, which is simplified as a normal distribution. Therefore, the flow *Order* when receiving the value defined by a normal distribution releases the need for products to be produced concerning the delivery planning horizon (*DesiredDelivery*). If the order is a contract (typically in VE), the *StandardDeviation* parameter is set to zero.

$$Order = \frac{NORMAL(Demand, StandardDeviation)}{DesiredDelivery} \tag{1}$$

where *Demand* represents a value corresponding to the total contracted demand; *StandardDeviation* represents a constant value that represents the contractual standard deviation defined for the demand fulfilment process; *DesiredDelivery* represents the contractual time defined for the fulfilment of the total demand.

For *SupplyManagement* the (A) Material Input loop, the idea is to establish enough material stock levels until all demand is met. For this, the model promotes the maintenance of material needs (*LotPurchaseRawMaterial*) defined by Eq. 2.

$$LotPurchaseRawMaterial = Order - \frac{NeedRawMaterial}{TimeOrderRawMaterial} \tag{2}$$

where $NeedRawMaterial$ represents the need for raw material concerning the production level. $TimeOrderRawMaterial$ represents the time required for the requested raw material to be available in stock, i.e. it refers to the purchase lead time.

Thus, it is possible to establish a relationship between the $SupplyManagement$ and $ProductionManagement$ subsystems, which occur in two distinct moments. $SupplyManagement$ is defined by $ProductionOrderReleased$ in Loop A $InputofMaterials$, presented in Eq. 3.

$$LotPurchaseRawMaterial = Order - \frac{NeedRawMaterial}{TimeOrderRawMaterial} \tag{3}$$

where $ProductionOrderReleased$ represents the release rate for consumption of production; $ProductionOrder$ represents the maximum amount of WIP for the process, which is proportional to production cycle time and desired production rate; $DemandExpectation$ represents the insertion of possible contractual variations for the VE production process; $ExtraTimeDemand$ represents the additional time to respond to variations caused by $DemandExpectation$.

The second point occurs through the Material Output loop (B), which establishes that a certain amount of material is released for production through the $RawMaterialRelease$, established by Eq. 4.

$$RawMaterialRelease = Delay\left(\frac{RawMaterial \times ProductStructure}{TimeOrderRawMaterial}, RawMaterialCoverageTime\right) \tag{4}$$

where $RawMaterialRelease$ represents the rate of use of raw material released for production; $RawMaterial$ represents the accumulation of raw materials; $ProductStructure$ represents the structure of the product used as the amount of materials used per unit of final product; $TimeOrderRawMaterial$ represents the time required for the requested material to be available in stock, that is, the purchase lead time; $RawMaterialCoverageTime$ represents index used to measure the time that the stock, in a given period, can cover the demand.

In $ProductionManagement$ the loop (C) WIP Control regulates the variation of the production rate concerning the input of material for production ($ConsumptionRawMaterial$), as observed in Eq. 5.

$$ConsumptionRawMaterial = (BatchRawMaterial - ProductionOrderReleased) \times ExtraProductionCapTime \tag{5}$$

where $ConsumptionRawMaterial$ represents the flow of the production process, representing the orders triggered for the production process; $BatchRawMaterial$ represents the flow of material to be released for each company participating in the VE; ProductionOrderReleased represents the release rate for consumption of production; ExtraProductionCap represents the ratio of available capacity to cycle time.

In Loop (D) Finished Product Output Control, represents finished product stock from $Production$, defined by Eq. 6:

$$Expedition = ExpProgr - ConclusionOrder \tag{6}$$

where $Expedition$ represents the rate of material available for delivery; $ExpProgr$ is the expected delivery rate; and $ConclusionOrder$ is the flow of scheduled order completion defined by the ratio between the normal delivery rate and maximum production rate.

In Loop (E), the $AverageDelay$ component, which aims to calculate an average ratio of the “Backlog”, represents the accumulation of final product that has not yet been delivered to the customer, that is, overdue products, allowing to establish reference values regarding the level of delay computed for the model, defined by Eq. 7:

$$AverageDelay = Mean(Backlog) \tag{7}$$

The $ManagementCapacity$ uses the $OrderPortfolio$ component corresponding to the actual demand to be met, composed of a line of products to be produced ($OrderEntry$) concerning those that are delivered ($OrderDelivery$), as shown in Eq. 8-10.

$$OrderEntry = Order \tag{8}$$

$$OrderDelivery = Expedition' \tag{9}$$

$$\begin{aligned} OrderPortfolio(t) = & OrderPortfolio(t - dt) + \\ & \int_0^t (OrderEntry - OrderDelivery)dt \end{aligned} \tag{10}$$

where $OrderPortfolio(t)$ represents the entry of orders in the company's backlog in period t; $OrderPortfolio(t - dt)$ the entry of orders in the company's backlog in the previous period; $OrderEntry$ represents the quantity of products to be inserted in the production; $OrderDelivery$ represents the amount of products finished by production.

Through the Loop (F) Capacity Control, $OrderPortfolio$ component establishes the required capacity from the relationship established with $IncCap$, which shows the need to increase the time available to meet real demand, as shown in Eq. 11.

$$IncCap = RelativeDemand + AdditionalTime \tag{11}$$

where $IncCap$ represents the increase in time to be made available to meet the real demand; $RelativeDemand$ is an indicator that relates demand with the entry of orders in the company's backlog; and $AdditionalTime$ is the time entry for available capacity.

5. Proof-of-concept case

5.1. *Presentation of the VE process*

This case is based on the need to meet a specific demand to produce a hammer developed with reusable material (handle and impact structure), used for glass assembly and to finish metal parts without damaging the product. From this, among 9 members participating in a VE, two companies were selected (company A and company B), where A had the competence to develop and manufacture biodegradable rubber and foam, and B specialised in the production of cast materials with ferrous or non-ferrous metal alloys. Both companies considered hammer production an interesting opportunity for product diversification. Thus, a cast aluminium handle was developed for the hammer, enabling the change of the impact part, as shown in Figure 3. As a result of this cooperation, the hammer developed was cheaper, lighter and had a longer life cycle. For years, it was sold to diverse European and American clients.

Initially, it was defined that the administrative members of VE would act as brokers for this VE formation process, and one of its main activities was to prepare the plan for the network's business opportunity. This plan integrated, among other things, the

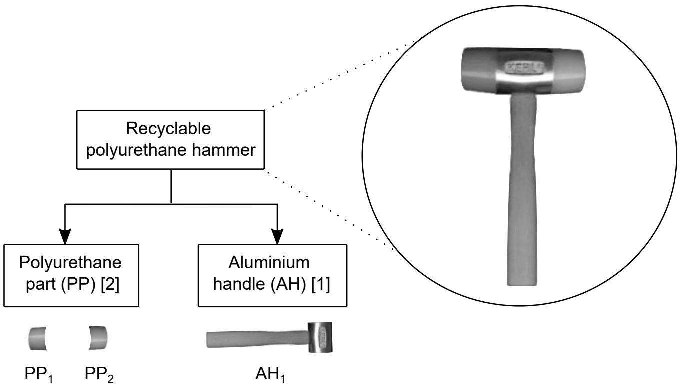


Figure 3. Hammer representation and build of materials (BOM)

capacities, costs, and delivery times of selected partners, in addition to distributing tasks within the VE. The conduct of the hammer project was divided into three distinct production phases: *ResinProduction*, *HandleProduction* and *FinalAssembly*. Each phase had to meet a specification level defined by the broker concerning the project's initial scope. It should be noted that, for the simulation model, the developed subsystems were combined according to the role of each VE member. Based on Table 2 and the partner selection, a set of macro-operations to be performed for VE operation was defined.

Table 2. Relation of tasks, duration time and precedence

Activity	Description	Duration (TU)	Precedence	Responsible enterprise
A	Planning	2	-	Members involved
B	Resin Production	1	A	Enterprise A
C	Handle Production	1	A	Enterprise B
D	Final assembly	1	B and C	Enterprise B

The resin production process is a combination of polyester resin reinforced with fibreglass divided into three stages. It starts with the preparation of the matrix paste, which goes through a thickening system generating semi-ready sheets that will later be shaped into the final part by compression moulding or injection moulding in heated metal moulds. The production of the handle is a process of injection of aluminium in a metallic matrix, in which the aluminium is injected with tremendous pressure to reach the complete filling of the mould and to be able to reproduce the most specific details. Final assembly ensures specification control and quality assurance.

5.1.1. Base cases

Initially, the baseline scenario (status quo) was created, and later, other simulations were performed with different conditions. The results allowed the team to assess in advance the possible impacts that some model variables would have on the behaviour of the S&OP-VE. The values assumed by the controllable variables of the base scenario are shown in Tab. 3. To create the base scenario, an initial demand (*Demand*) of 5000 units of the hammer was adopted, with the desired delivery time (*DesiredDelivery*) of 12-time units (TU), thus a twelve-period simulation horizon was considered. In addition, it was adopted that both companies would receive inputs in the same period, and their consumption occurs according to a sequential schedule of activities, but since delays are possible, a 15 TU was considered.

Table 3. Controllable variables for the base scenario

Variables	Unit	Description	Enterprise A	Enterprise B
RawMaterialCoverageTime	Time	Raw material stock coverage time	1	2
TimeOrderRawMaterial	Time	Purchasing lead time	1	2
ProductStructure	Quantity	Quantity of materials used per unit of the final product	1	2
Demand	Quantity	Total contracted demand.	5000	-
StandardDeviation	Dimensionless	Contractual standard deviation to meet demand	0.1	-
DesiredDelivery	Time	Constant representing the contractual time defined for meeting the total demand.	12	12
DemandExpectation	Quantity	It represents the insertion of possible contractual variations to the VE production process.	1	1
ExtraTimeDemand	Time	It represents the additional time to meet the variations caused by *DemandExpectation*.	1	1
SafetyStock	Time	It represents the amount of time that the company would like to hold stock.	0	0
CycleTime	Time	It represents the time required to complete a sequential production process.	1	2
TimeReduction	Time	Constant representing the time reduction to available capacity.	0	0
AdditionalTime	Time	Constant representing the time insertion for the available capacity.	1	1

The simulation results were evaluated by calculating the following stock type variables. Inventory management among partner companies, through $RawMaterial$ (Eq. 12) for the acquisition of materials, and the $Backlog$ (Eq. 13) to meet demand. Production management among partner companies, through WIP (Eq. 14) and $FinishedProduct$ (Eq. 15). Capacity management through $AvCap$ (Eq. 16).

$$\begin{aligned} RawMaterial(t) =& RawMaterial(t-dt) + \\ & \int_0^t (LotPurchaseRawMaterial - RawMaterialRelease)dt \end{aligned} \tag{12}$$

where $RawMaterial(t)$ represents the accumulation of raw materials in time t; $RawMaterial(t-dt)$ represents the accumulation of raw materials in the previous period; $LotPurchaseRawMaterial$ indicates the number of items to be inserted in the supply process; and $RawMaterialRelease$ represents a rate of use of raw material released for production.

$$Backlog(t) = Backlog(t-dt) + \int_0^t (Entry - Expedition')dt \tag{13}$$

where $Backlog(t)$ represents the accumulation of final products the customer did not receive, that is, expired products in time t; $Backlog(t-dt)$ Represents the accumulation of final products the customer did not receive, that is, expired products in the previous period; $Entry$ represents the volume of products that the system will process; $Expedition$: represents the rate of material available for delivery.

$$WIP(t) = WIP(t-dt) + \int_0^t (ConsumptionRawMaterial - Production)dt \tag{14}$$

where $WIP(t)$ represents the accumulation of material in the process in time t; $WIP(t-dt)$ represents the accumulation of material in the process in the previous period; $ConsumptionRawMaterial$ marks the beginning of the production process, representing the orders triggered for the production process; $Production$ represents the production rate in the item quantity per time ratio.

$$FinishedProduct(t) = FinishedProduct(t - dt) + \int_0^t (Production - Expedition)dt \quad (15)$$

where $FinishedProduct(t)$ represents the accumulation of the finished product in time t; $FinishedProduct(t - dt)$ represents the accumulation of the finished product in the previous period; $Production$: represents the production rate in the item quantity per time ratio; $Expedition$ represents the rate of material available for delivery.

$$AvCap(t) = AvCap(t - dt) + \int_0^t (IncCap - CapRed)dt \quad (16)$$

where $AvCap(t)$ represents the accumulation of time to be made available to meet the actual demand for contracts in time t; $AvCap(t-dt)$ indicates the accumulation of time to be made available to meet the actual demand for contracts in the previous period; $IncCap$ represents the increase in time to be made available to meet the real demand; $CapRed$ represents the reduction in the time available to meet the real demand.

To that effect, key production control and inventory management decisions adopted by companies include order fulfilment (which determines the ability to meet customer orders based on inventory adequacy) and production scheduling (determination of the start of production based on the enterprise's demand and inventory position). The first stock-type variable evaluated was $RawMaterial$, which represents the accumulation of raw materials in the $SupplyManagement$ process. According to the results of the base scenario, the behaviour of $RawMaterial$ presents the oscillation in Fig. 4.

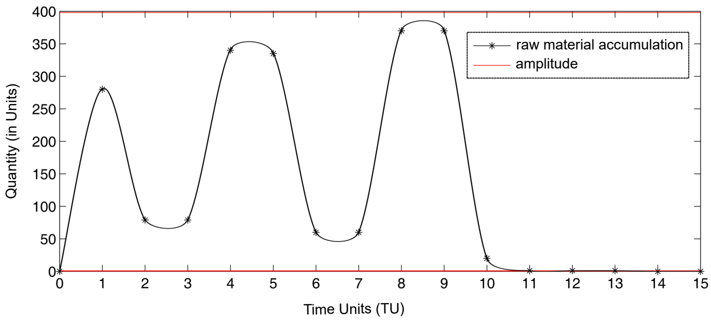
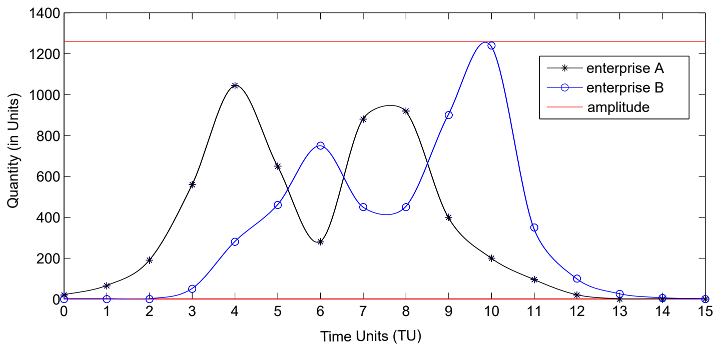


Figure 4. Stock variable $RawMaterial$ (Supply Management)

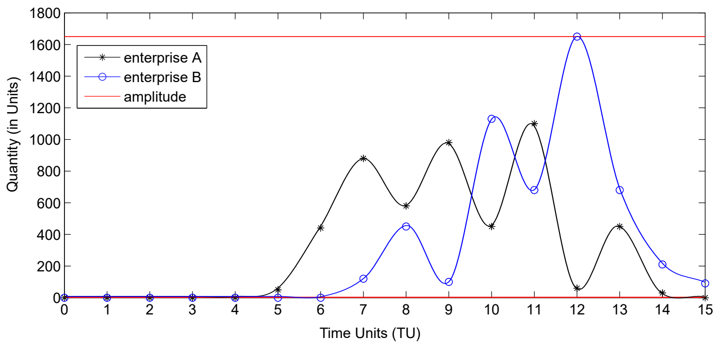
$RawMaterial$ values oscillate according to the maximum amplitude (Max. Ampl.) of 398 (quantity) and the minimum (Min. Ampl.) of 0 (quantity). This behaviour is a standard for inventory components, in which the frequency and shape represent a self-sustaining oscillation, also called the *limitcycle* (Sterman 2010). Considering the model characteristics, only one order for $SupplyManagement$ was used. In other words, there is no $RawMaterial$ for both enterprises, as the raw material acquisition process would be carried out jointly by the companies. It is noticed that during periods 3, 7 and 10 the values obtained for the $RawMaterial$ are at a low point (inventory depletion), while periods 1, 5 and 9 represent material acquisition (i.e., supply) according to the need of the VE operating process.

The behaviour of the WIP variable, represented in Fig. 5a, characterises the relationship between production and the need for materials ($RawMaterial$).

The behaviour shown in Fig. 5a indicates that the $ProductionManagement$ con-



(a) Stock variable "WIP" (Production Management)



(b) Stock variable "FinishedProduct" (Production Management)

Figure 5. WIP and FinishedProduct (Production Management)

trol structure allows WIP oscillations to alternate between companies. Enterprise B presents its maximum production oscillation only in period 10 due to the delay function used in the flow variable called *Production*. Thus, the natural behaviour of enterprise B tends to generate a possible delay during the VE production process since the process in B occurs after A. According to Sterman (2010), this behaviour of the WIP component is one of three possibilities in supply chains (oscillation, amplification, and delay in the peak phase). According to the same author, the amplitude of fluctuations often increases as they propagate through the sequential processes of participating companies, with each upstream step in a supply chain tending to lag its immediate client. Considering the WIP results obtained for both companies, Fig. 5b represents the results for the finished product stock variable defined as $FinishedProduct$.

Like the WIP component, Fig. 5b shows that the behaviour of the $FinishedProduct$ is related to the capacity of the original model to generate products to meet the programmed demand. Thus, considering the maximum point for enterprise B arriving only in period 12, it is concluded that the base scenario is experiencing delays, thus the expected values for this variable would not be close to zero in period 12, to respect the delivery deadline. Based on this result, the *Backlog* stock variable confirms the delay trend, as can be seen in Fig. 6. It is possible to verify that the *Backlog* variable for enterprise B reacts quickly, oscillating and promptly returning to a steady state. In this behaviour, one can observe that the oscillation effect is a consequence of the delay in the production structure, which presented 260 units overdue in period 13. However, the causal link relationships in the model lead the system state to converge to equilibrium at the end of the simulation period as expected, according to Sterman (2010).

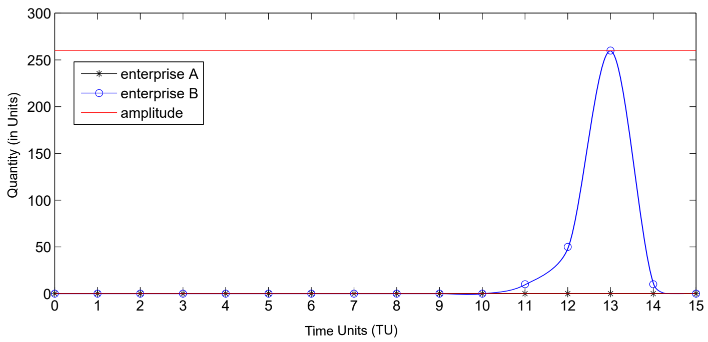


Figure 6. Stock variable *Backlog* (Production Management)

Fig. 7 presents the available capacity, i.e., *AvCap*. As Sterman (2010) proposed, the available capacity responds to the production levels, gradually increasing towards the end of the simulation period. For the same author, this is because companies tend not to reduce working hours below normal (especially when they are contractually obliged to pay for a full period).

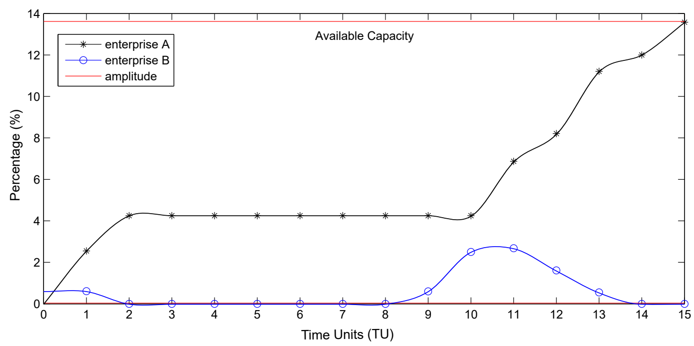


Figure 7. Stock variable *AvCap* (Capacity management)

It is possible to notice that the capacity varies substantially, and enterprise B has a high occupancy rate, leaving little room for flexibility. Based on the results obtained for the base scenario, Table 4 identifies the average value and amplitude for each variable analysed in the base scenario.

Table 4. Results for the base scenario

Variable	Enterprise	Average	Min.	Max.
RawMaterial	A	126.36	0	398
	B	126.36	0	398
WIP	A	378.53	0	1300
	B	365.71	0	1100
FinishedProduct	A	358.57	0	1700
	B	365.00	0	1150
Backlog	A	0.00	0	0
	B	23.57	0	260
AvCap	A	6.37%	0	14%
	B	0.57%	0	3%

5.2. *S&OP - VE performance*

To illustrate the performance of S&OP-VE, we proposed scenarios that will change the model's input variables to test possible delay reductions and eliminate the customer service problem (backlog). The hypotheses tested for the input variables were defined as follows:

- Scenario 1: Increase enterprise B's available capacity by 50%.
- Scenario 2: Increase enterprise B's available capacity by 100%.
- Scenario 3: Add a safety stock for enterprise B.
- Scenario 4: Include an additional time to meet demand.
- Scenario 5: Reduce by half the production cycle time for VE companies.
- Scenario 6: Introduce a new member in VE.

These scenarios were defined based on general characteristics and the possible decision level for the aggregate planning since in this planning process, the quantities to be produced in the medium term are defined by adjusting the production speed, available labour, stocks, and other parameters to meet demands, using the resources available in the enterprise.

The first and second simulated scenarios were defined based on the hypothesis that increasing the available time capacity in enterprise B (for example, through the introduction of overtime, or a new shift or the hiring of new employees) could solve the unwanted Backlog. In this case, the addition of time in the variable $AvCap_B$ would cause a reduction in the delay observed in the base scenario, in addition to generating better results for the performance of the variables related to production management (WIP and $FinishedProduct$). The third scenario concerns increased finished product safety stock in enterprise B, avoiding shortages through demand variability. For the fourth scenario, the hypothesis is that when renegotiating delivery times, the operational results of VE would be better distributed throughout the simulation period, avoiding delays in product delivery. To account for this, 8 additional periods were included in the simulation process ($ExtraTimeDemand = 8(Time)$). In the fifth scenario, the hypothesis is that it would be possible to reduce the delay through improvements in production processes in both VE partners (e.g. reducing production lead time through Lean Manufacturing implementation). Finally, in the sixth scenario, the hypothesis tested is that when inserting a partner in the VE to carry out the final manufacturing process, removing enterprise B from executing two productive operations, the delay would be reduced.

The average and minimum and maximum values were used for each stock variable analysed in the base scenario to evaluate the scenarios' performance. Results for all scenarios are shown in Table 5.

Scenarios 1 and 2 have similar characteristics, as they represent company B's increased available capacity. With this, there is a reduction in the *Backlog* variable of 39.37% and 78.78% respectively, as well as an increase in the average rate of available capacity ($AvCap_B$) of the order of 107.33% for company B in scenario 2. Such behaviour confirms the hypothesis that the periodic addition of time in $AvCap_B$ allows for increasing the performance of production variables related to company B, reducing the delay in the order delivery ($Backlog_B$).

In scenario 3, it is observed that the increase in the use of the $RawMaterial$ variable influenced the decrease in the overall average of the *Backlog* by about 21.34% compared to the base scenario. In this scenario, there was no significant change in the $FinishedProduct$ variable for both companies, demonstrating that the *Backlog* re-

Table 5. Results for the base scenario

		Scenario 1		Scenario 2		Scenario 3		Scenario 4		Scenario 5	
Variable	Ent.	Aver.	Max.	Aver.	Max.	Aver.	Max.	Aver.	Max.	Aver.	Max.
RawMaterial	A	137.40	510	145.57	550	152.07	590	71.76	350	149.50	590
	B	137.40	510	145.57	550	152.07	590	71.76	350	149.50	590
WIP	A	378.50	1250	364.21	1050	378.5	1300	21.67	900	339.93	1100
	B	372.80	1200	377.86	1000	381.07	1400	261.90	1200	345.36	1500
FinishedProduct	A	352.10	1400	332.86	1250	357.06	1300	244.76	850	344.29	1350
	B	360	1200	354.29	1400	367.86	1400	229.76	1190	306.43	1350
Backlog	A	0	0	0	0	0	0	0	0	0	0
	B	14.20	180	5	50	18.57	200	0.95	0	3.57	40
AvCap	A	6.60%	13.9%	7.37%	15.89%	6.37%	13.9%	26%	50%	7.22%	16%
	B	1.8%	4.5%	2.25%	6.5%	1.42%	4.00%	4%	20%	3.31%	10.2%

Note: Ent. - Enterprise; Aver. - Average; Max. - Maximum.

duction occurred according to the safety stock without any impact on the other stock variables.

Despite the reduction in delay, when compared to the other scenario, scenario 3 has a lower impact on all studied components. For scenario 4, an interesting behaviour was observed, as with the reconsideration of delivery times, the *RawMaterial*, *WIP* and *FinishedProduct* components showed substantial reductions, including the *Backlog* that reached a reduction of around 94, 85%. This hypothesis proves that the adjustment in the time for delivery of materials had a relevant impact on the model's performance, not only reducing the delay in the base scenario but also increasing the average available capacity for company B in the order of 138%.

Since scenario 6 requires the introduction of another partner in the VE, its results are shown in Table 6.

Table 6. Results for scenario 6

		Scenario 6		
Variable	Enterprise	Average	Min.	Max.
RawMaterial	A	243.62	0	1100
	B	243.62	0	1100
	C	243.62	0	1100
WIP	A	335.63	0	2100
	B	338.15	0	2100
	C	310.63	0	2100
WIP	A	317.81	0	2400
	B	330.63	0	2100
	C	316.88	0	1700
Backlog	A	0	0	0
	B	0	0	0
	C	0	0	0
AvCap	A	6.83%	0	16.00%
	B	3.36%	0	12.00%
	C	5.68%	0	21.00%

Note: Ent. - Enterprise; Aver. - Average; Max. - Maximum.

To determine the effects of each hypothesis on each stock variable, comparative analyses of each scenario with the base scenario were performed. Comparative results are shown in Table 7, in which positive values (+) represent an increase in variable averages, while negative values (-) represent a reduction. As seen in Table 7, all scenarios showed a reduction in the *Backlog* variable, which shows that all hypotheses possibly satisfy the delay reduction.

Table 7. Comparative analysis of simulated scenarios for enterprises A and B

Variable		Scenario						
		Base	1	2	3	4	5	6
RawMaterial	A	126.36	+8.76%	+15.20%	+20.34%	-43.20%	+18.07%	-11.33%
	B	126.36	+8.76%	+15.20%	+20.34%	-43.20%	+18.07%	-11.33%
WIP	A	378.53	0	-3.78%	0.00%	-10.19%	-42.76%	-7.54%
	B	365.71	+19.55%	+33.07%	+4.29%	-5.56%	-28.33%	-12.39%
FinishedProduct	A	358.57	-1.17%	-7.16%	-0.02%	-3.98%	-31.73%	-9.41%
	B	365	-1.36%	-2.94%	+0.01%	-16.04%	-37.05%	-16.04%
Backlog	A	0	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
	B	23.57	-39.37%	-78.78%	-21.34%	-94.85%	-100.00%	-100%
AvCap	A	6.61%	+3.76%	+13.56%	0.00%	+18.68%	200%	200%
	B	1.89%	+73.39%	+107.33%	+30.27%	+138.00%	200%	150%

6. Discussion

6.1. *Discussions concerning numerical results*

To explore the model's ability to provide insights, it is possible to realise that Scenarios 1 and 2 present similar characteristics since they represent an increase in the available capacity for enterprise B. *Backlog* was reduced by 39.37% and 78.78% respectively. In contrast, an increase of 107.33% in the average available capacity rate ($AvCap_B$) for enterprise B in scenario 2 is observed. This behaviour confirms the hypothesis that additional $AvCap_B$ allows for increasing the performance of the production variables referring to enterprise B, reducing the delays in the order delivery ($Backlog_B$). These results demonstrate that the increase in capacity availability in company B is not directly related to the reduction in delay found in the base scenario, in addition to generating better results for the performance of variables related to production management (WIP and PA).

In scenario 3, it is observed that the increased use of $RawMaterial$ variable influenced the decrease of 21.34% in the overall average *Backlog* of the base scenario. It is noticed that, in this scenario, there was no significant change in the $FinishedProduct$ variable for both companies, demonstrating that the reduction in *Backlog* occurred according to the safety stock without any impact on the other stock variables. Despite the delay reduction, scenario 3 has less impact on all analysed components compared to the other scenarios.

For scenario 4, an interesting behaviour was observed since, with the reconsideration of delivery times, the components $RawMaterial$, WIP and $FinishedProduct$ showed substantial reductions. *Backlog* reached a reduction of 94,85%. This hypothesis proves that the adjustment in material delivery time had a relevant impact on the model performance, reducing the delay of the base scenario and increasing the average of the available capacity for enterprise B by 138%. Among the variables in scenario 4, the one that demonstrated a substantial behaviour change was the available capacity ($AvCap$) for enterprise A, thus we decided to depict it in Fig. 8.

It is observed that, in the base scenario, the behaviour of $AvCap$ for enterprise B does not exceed the value of 3%, which leaves little margin for any contingency. As for scenario 4, the same variable acts at low-capacity levels during the initial simulation periods, but from period 12 onwards, it is possible to notice an important increase. Scenarios 5 and 6 show the best results, emphasising the total reduction of the average *Backlog* and the maximum use of the available capacity for both enterprises in the VE. As shown in Fig. 9, the general capacity increases from the sixth simulation period due to the changes proposed for both scenarios. In scenario 5, the hypotheti-

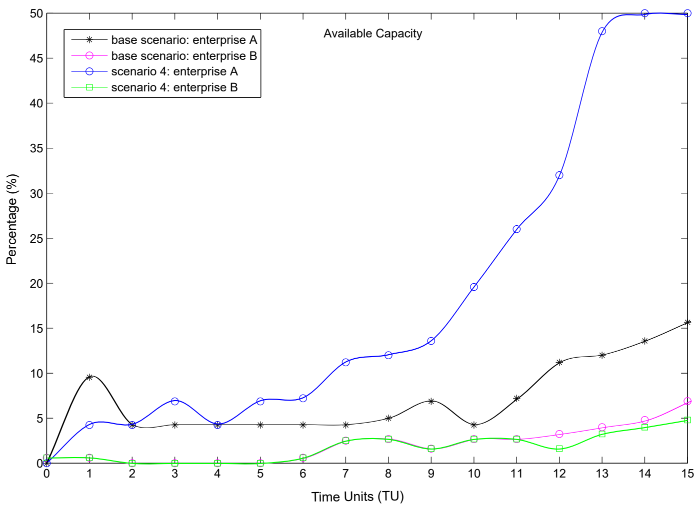


Figure 8. Comparison of *AvCap* in the base scenario and scenario 4

cal productive improvements to reduce production lead times were effective from the seventh simulation period, increasing the availability for VE operation. In addition, introducing a new partner, as proposed in scenario 6, expands the available capacity of all VE members.

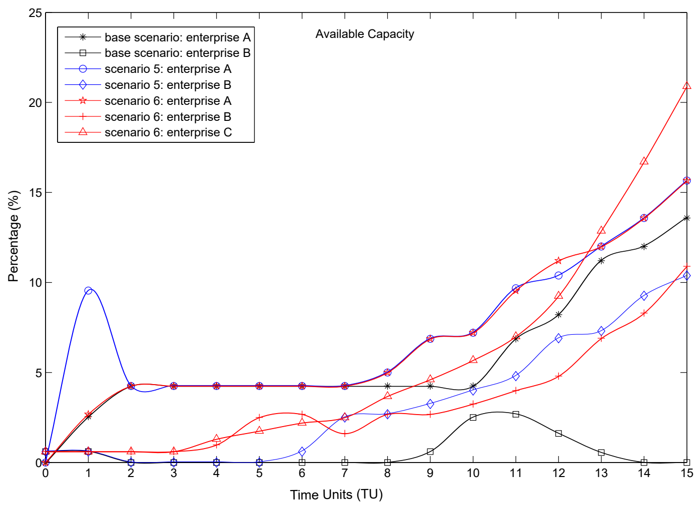


Figure 9. Comparison of *AvCap* in the base scenario and scenarios 5 and 6

In the base scenario, the behaviour of the variable *AvCap* for company B does not exceed the value of 3%, leaving little room for unforeseen events. As for scenario 4, the same variable acts at low levels of capacity during the initial simulation periods, but from period 12 onwards, it is possible to notice an important increase. Scenarios 5 and 6 present the best results, emphasising the total reduction in the average of the *Backlog* variable and the maximum use of the available capacity for the companies that form VE. It is worth highlighting the behaviour of the available capacity, as shown in Fig.9, where it is observed from the sixth simulation period onwards, an available capacity increases because of changes for both scenarios. In scenario 5, the hypothetical productive improvements for reducing production lead times took effect from the seventh simulation period, increasing the availability for the operation of the

VE. Together, the introduction of the new partner as proposed in scenario 6 expands the available capacity of all VE members.

6.2. *Discussions concerning the use of the proposed model*

The results of our research contribute to the body of literature, as it proposes a way to combine current SD knowledge on the VE creation/operation process. The developed S&OP-VE allows researchers and practitioners in both domains to increase their understanding of the effects of changing parameters to select partners for VE formation with manufacturing characteristics. In addition, usefulness and ease of use were also demonstrated in this case. In terms of usefulness, this experience shows how the traditional S&OP, which is usually limited to more static analysis, may be improved to obtain a more dynamic approach, favouring an analytics-oriented decision-making process. This is particularly important for enterprises facing Industry 4.0 challenges. For example, simulation results in the two previous subsections suggest different performances for the studied scenarios, in which scenarios 5 and 6 provide superior efficiency compared to the results of the other scenarios. Achieving these results would be much more time-consuming with traditional spreadsheet-based S&OP (still not able to capture the feedback-loop phenomenon properly) compared to the process and results from generation time of S&OP-VE, suggesting that the proposed approach offers superior ease of use. The possibility of changing behaviours was translated into a dashboard and control cockpit (Fig. 10), in which modifications in the model are allowed.

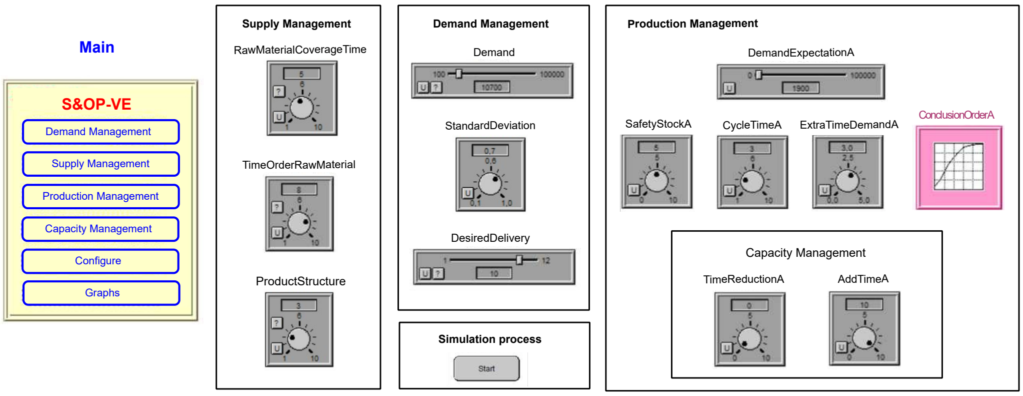


Figure 10. Main Menu and control cockpit of S&OP-VE.

These dynamic analyses allow for multiple future state scenario creation on the fly during executive S&OP-like meetings, generating simulation results in a few minutes, thus contributing to the decision-making abilities of the planning team of the entire VE. The analysis of data in tables and graphical behaviours are related to the ability of the S&OP-VE model to provide data supporting decision-making, a capability provided by the SD methodology. Furthermore, such formats are functional as they can be easily integrated into databases, thus allowing the better organisation of strategic planning processes for VE members. Both utility and ease of use were illustrated in this case-based study. As for usefulness, this experience demonstrated how the traditional S&OP methodology limited to static analysis could be extended to a more dynamic approach capturing complex feedback loops, providing additional analytical skills for companies that want to gain a competitive advantage, which can be interesting for companies living in an Industry 4.0 context.

The S&OP-VE developed in this article represents a decision support system for selecting/operating companies in the VE format. The model developed can be considered a generic model that can be theoretically calibrated for any participating company by changing the model's parameters. The analysis of the results allows the VE members to plan actions related to the data obtained from the simulation. It is noteworthy, for example, that increasing the available capacity in one of the members allows for improving the performance of the production variables related to it, reducing the delay in the delivery of the order, but this can cause changes in the productive paradigms of the company, requiring the acquisition of resources. The same cannot be seen when the proposition is to increase the safety stock, which reduces the delay in the delivery of the order without causing changes in the partners' production system. It was even possible to verify different levels of impact by inserting a new participating member. This analysis can be translated into specific management policies for the VE, e.g. related to safety stocks and capacity occupation.

The results obtained with the proof-of-concept allow for expanding the understanding of the complex relationship between companies in a VE scenario, allowing us to infer productive behaviours related to capacity, production levels, and material supply and their consequences on customer service levels. In addition, the results generate valuable insights for corporate learning, considering the generation of a fundamental framework to define actions that can be understood within a systemic framework, expanding the scope of decision-making, and reducing the gap in aggregate planning methods for this collaborative network.

The simulation model presented in this article provides a wide range of possible benefits that should result in efficiency and savings gains for selecting partners and even for defining operational characteristics among them. However, the assumption that efficiency gains always result in corresponding resource savings (e.g. time and labour costs) is not valid, particularly when looking at the results provided in scenarios 1 and 2. Besides these benefits, some limitations of this research should also be mentioned. First, the proposed model focuses only on the tactical level, limiting its applicability to other decision-making levels. In addition, this model's applicability is also limited to the assumptions and granularity levels explained in Section 2.

7. Conclusions

Even though the literature provides some models and tools to assist in operations carried out during the life cycle of VE, there are still research gaps that have not been appropriately addressed, especially concerning the planning and control of shared production processes, particularly at the tactical level. In this context, a novel S&OP-VE model was proposed using System Dynamics as an artefact allowing production planners to analyze a complex reality of the selection/operation of VEs, thus supporting decision-making. Specifically, this work contributed to improving the agility and success of VE through the development of structures that contribute to the understanding of the phenomenon of aggregated planning within VE, allowing the creation of a fundamental knowledge framework for the decision-making of VE.

A real-scale proof-of-concept case was done to demonstrate the model's utility and ease of use for decision-makers, allowing for identifying behaviour patterns of the whole system and its constituent parts. The study highlights that the analytical function of S&OP-VE contributes to improvements in the operational capacity of the participating companies, as well as to deal with different scenarios and react accordingly. In what follows, we summarize the main advantages of using the proposed approach:

- Favouring shared actions within the VE: the proposed model allows us to perform a comparative analysis of different S&OP scenarios, testing different hypotheses for a future shared action among VE partners to face some capacity management challenges.
- A systemic view of a complex phenomenon: the proposed model is a combination of different modules for each VE partner; thus, it is possible to understand the behaviour of each partner while having a global view of the whole system.
- Decision agility for hypotheses testing: The VE partners can use the proposed model to adjust their S&OP quickly. Simulation testing and analysis may sometimes be run in minutes, depending on the number of parameters involved in the decision-making process. For example, the proposed approach can be employed during S&OP planning meetings, such as during the executive sessions of a Sale & Operations Planning (S&OP) process.
- Diversity of simulation scenarios: SD models favour the construction of several scenarios and testing numerous hypotheses. With this possibility, the universe of options in the decision-making process for VE increases.

Like other scientific work, this research has several limitations. Considering the results of our simulation experiment, although the simulation model is developed and tested within a real case study, it fails to capture the reality of the natural system in all its complexity. In addition, the quantification step requires assumptions about expected cause-and-effect relationships and some values were assigned to factors without empirical data. More specifically, empirical evidence should be presented in real cases to demonstrate whether the observed data fit the simulated data. In addition, we made simplifying assumptions that more realistic input factors can override. For example, the model can be improved by adding new stocks, variables, or flows based on specific characteristics to be developed from new demand perspectives.

Future research may focus on modelling operational-level decision-making and providing decision support in other scenarios and with different operational conditions. Furthermore, in the context of Industry 4.0 and the Internet of Things, the proposed model can be adapted for highly distributed environments, that is, for VEs with many partners and different objects of interaction. However, this level of interaction requires a set of information related to the integration of information systems. The challenge of integrating systems for the operation of a VE is highly complex and can be explored in future research, mainly related to the ways of sharing data of different types (structured or semi-structured). Another challenge that needs to be examined is in the process of data collection and processing in information systems distributed among the VE members, mainly due to technological and cultural differences among the participating members. In the experimental part, it is recommended to compare with other advanced theories or methods to highlight the progressive nature of the proposed S&OP-VE. Robustness and resilience are topics of extreme relevance to operationalizing a VE, but they are outside the scope of our article, allowing a research gap to be explored. Future research on S&OP for VE may also focus on modelling new features left out of the scope of this study, such as human, social and cultural factors. As suggested by Ogbeyemi et al. (2021), the design of S&OP systems should consider human factors (e.g., job skill, job satisfaction, job fatigue, and job rotation) since it influences jobs and system performance. Likewise, several authors suggest that

S&OP systems should also consider social and economic factors since they can affect the activities between partners of a VE and the performance of these systems (Giret et al. 2015; Pérez-Campdesuñer et al. 2021; Zarte 2022).

Declarations

Competing interests

The authors declare no competing interests.

Funding

This research is partially supported by Mitacs through the Mitacs Accelerate program in Canada.

Availability of data and material

The datasets generated during and/or analysed during the current study and the model are available from the corresponding author on reasonable request.

Consent for publication

All authors have approved and have agreed to submit the manuscript to this journal.

Authors' contributions

Rodrigo Furlan de Assis: conceptualisation, methodology, data collection, formal analysis, visualisation, writing - original draft, writing - review and editing. Luis Antonio de Santa-Eulalia: conceptualisation, methodology, supervision, formal analysis, validation, writing - review and editing. Fabiano Armellini: validation, writing - review and editing. Rosley Anholon: validation, writing - review and editing. Izabela Simon Rampasso: validation, writing - review and editing. Fabio Müller Guerrini: validation, writing - review and editing. Moacir Godinho Filho: formal analysis, validation, writing - review and editing. William de Paula Ferreira: formal analysis, methodology, visualisation, funding acquisition, supervision, writing - review and editing.

Code availability

Not applicable.

Ethics approval

Not applicable.

Consent to participate

Not applicable.

References

Bokolo Anthony Jnr and Sobah Abbas Petersen. Examining the digitalisation of virtual enterprises amidst the covid-19 pandemic: a systematic and meta-analysis. *Enterprise Information Systems*, 15(5):617–650, 2021.

Nikitas A Assimakopoulos, Anastasis N Riggas, and Konstantinos D Karropoulos. A systemic methodology via system dynamics for a virtual enterprise architecture constructing wireless payments. *International Journal of Learning and Change*, 1(3):362–376, 2006.

Mary Bajomo, Akinola Ogbeyemi, and Wenjun Zhang. A systems dynamics approach to the management of material procurement for engineering, procurement and construction industry. *International Journal of Production Economics*, 244:108390, 2022.

Heiko Baum and Jens Schütze. An organizational concept for collaborative enterprise networks. *Procedia CIRP*, 7:55–60, 2013.

Andrei Borshchev. *The big book of simulation modeling: multimethod modeling with AnyLogic 6*. AnyLogic North America, 2013.

Carlos F Bremer, Flávia VS Michilini, Jairo EM Siqueira, and Luciane M Ortega. Virtec: An example of a brazilian virtual organization. *Journal of Intelligent Manufacturing*, 12(2): 213–221, 2001.

Luis M Camarinha-Matos. Collaborative networks in industry and the role of pro-ve. *International Journal of Production Management and Engineering*, 2(2):53–56, 2014.

Luis M Camarinha-Matos and Hamideh Afsarmanesh. A comprehensive modeling framework for collaborative networked organizations. *Journal of Intelligent Manufacturing*, 18(5):529–542, 2007.

Luis M Camarinha-Matos, Hamideh Afsarmanesh, Nathalie Galeano, and Arturo Molina. Collaborative networked organizations–concepts and practice in manufacturing enterprises. *Computers & Industrial Engineering*, 57(1):46–60, 2009.

JDA Carvalho, NA Moreira, and LCM Pires. Autonomous production systems in virtual enterprises. *International Journal of Computer Integrated Manufacturing*, 18(5):357–366, 2005.

H Castro, GD Putnik, V Shah, and MM Cruz-Cunha. A simulation tool and its role in supporting the management of the transformation processes of traditional enterprises into virtual enterprises. *Tékhne*, 10(2):99–111, 2012.

Ricardo Chalmeta and Reyes Grangel. Performance measurement systems for virtual enterprise integration. *International Journal of Computer Integrated Manufacturing*, 18(1):73–84, 2005.

Ali Cheraghalikhani, Farid Khoshalhan, and Hadi Mokhtari. Aggregate production planning: A literature review and future research directions. *International Journal of Industrial Engineering Computations*, 10(2):309–330, 2019.

XN Chu, SK Tso, WJ Zhang, and Q Li. Partnership synthesis for virtual enterprises. *The International Journal of Advanced Manufacturing Technology*, 19(5):384–391, 2002.

José Crispim, Nazaré Rego, and Jorge Pinho de Sousa. Stochastic partner selection for virtual enterprises: a chance-constrained approach. *International Journal of Production Research*, 53(12):3661–3677, 2015.

Rodrigo Furlan de Assis, Luis Antonio de Santa-Eulalia, William de Paula Ferreira, Fabiano Armellini, Rosley Anholon, Izabela Simon Rampasso, and João Guilherme Cruz Lopes dos Santos. Translating value stream maps into system dynamics models: a practical framework. *The International Journal of Advanced Manufacturing Technology*, 114(11):3537–3550, 2021.

William de Paula Ferreira, Fabiano Armellini, and Luis Antonio De Santa-Eulalia. Simulation in industry 4.0: A state-of-the-art review. *Computers & Industrial Engineering*, 149:106868, 2020.

William de Paula Ferreira, Arun Palaniappan, Fabiano Armellini, Luis Antonio de Santa-Eulalia, Elaine Mosconi, and Guillaume Marion. Linking industry 4.0, learning factory and simulation: Testbeds and proof-of-concept experiments. *Artificial Intelligence in Industry 4.0: A Collection of Innovative Research Case-studies that are Reworking the Way We Look* *at Industry 4.0 Thanks to Artificial Intelligence*, pages 85–96, 2021.

William de Paula Ferreira, Fabiano Armellini, Luis Antonio de Santa-Eulalia, and Vincent Thomasset-Laperrière. Extending the lean value stream mapping to the context of industry 4.0: An agent-based technology approach. *Journal of Manufacturing Systems*, 63:1–14, 2022a.

William de Paula Ferreira, Fabiano Armellini, Luis Antonio de Santa-Eulalia, and Vincent Thomasset-Laperrière. A framework for identifying and analysing industry 4.0 scenarios. *Journal of Manufacturing Systems*, 65:192–207, 2022b.

Yusi Ding, Yang Gao, and Gen Luo. Virtual enterprise global production planning based on cost optimization with time constraints. In *2009 International Conference on Management and Service Science*, pages 1–4. IEEE, 2009.

Stephen M Disney, Mohamed Mohamed Naim, and A Potter. Assessing the impact of e-business on supply chain dynamics. *International Journal of production economics*, 89(2): 109–118, 2004.

Christopher Durugbo. Collaborative networks: a systematic review and multi-level framework. *International Journal of Production Research*, 54(12):3749–3776, 2016.

Shady Elmasry, Mohamed Shalaby, and Mohamed Saleh. A system dynamics simulation model for scalable-capacity manufacturing systems. *International Conference of the System Dynamics Society*, 2012.

Jay Wright Forrester. Industrial dynamics. *Journal of the Operational Research Society*, 48 (10):1037–1041, 1997.

Angelita Moutin Segoria Gasparotto and Fábio Müller Guerrini. A practical management model for supporting virtual organizations creation within their breeding environments. In *Working Conference on Virtual Enterprises*, pages 137–144. Springer, 2013.

Patroklos Georgiadis and Charalampos Michaloudis. Real-time production planning and control system for job-shop manufacturing: A system dynamics analysis. *European Journal of Operational Research*, 216(1):94–104, 2012.

Adriana Giret, Damien Trentesaux, and Vittal Prabhu. Sustainability in manufacturing operations scheduling: A state of the art review. *Journal of Manufacturing Systems*, 37:126–140, 2015.

Hongmei Gou, Biqing Huang, Wenhuang Liu, and Xiu Li. A framework for virtual enterprise operation management. *Computers in Industry*, 50(3):333–352, 2003.

Christiane Peres Goulart, Luis Antonio Santa Eulalia, and Carlos Frederico Bremer. Determinação das atividades de planejamento e controle da produção em empresas virtuais. *Anais*, 2000.

Alan R Hevner. A three cycle view of design science research. *Scandinavian journal of information systems*, 19(2):4, 2007.

Min Huang, Ruixian Huang, Bo Sun, and Linrong Li. Research on the production scheduling optimization for virtual enterprises. *Mathematical Problems in Engineering*, 2013, 2013.

Luca Iandoli, Cristina Ponsiglione, Elio Marchione, and Giuseppe Zollo. Knowledge exchange processes in industrial districts and the emergence of networks. *Central European Journal of Operations Research*, 20(2):231–250, 2012.

Aboozar Jamalnia, Jian-Bo Yang, Ardalan Feili, Dong-Ling Xu, and Gholamreza Jamali. Aggregate production planning under uncertainty: a comprehensive literature survey and future research directions. *The international journal of advanced manufacturing technology*, 102 (1):159–181, 2019.

Martin Kunc. System dynamics: a soft and hard approach to modelling. In *2017 Winter Simulation Conference (WSC)*, pages 597–606. IEEE, 2017.

Rafael Marques, William de Paula Ferreira, Georges Nassif, Fabiano Armellini, Jeffrey Dungen, and Luis Antonio de Santa-Eulalia. Exploring the application of iot in the service station business. *IFAC-PapersOnLine*, 54(1):402–407, 2021.

John DW Morecroft. *Strategic modelling and business dynamics: A feedback systems approach.* John Wiley & Sons, 2015.

Sina Nayeri, S Ali Torabi, Mahdieh Tavakoli, and Zeinab Sazvar. A multi-objective fuzzy robust stochastic model for designing a sustainable-resilient-responsive supply chain network. *Journal of Cleaner Production*, 311:127691, 2021.

Akinola Ogbeyemi, Wenjun Lin, Forrest Zhang, and Wenjun Zhang. Human factors among workers in a small manufacturing enterprise: a case study. *Enterprise Information Systems*, 15(6):888–908, 2021.

Latifa Ouzizi, Didier Anciaux, Marie Claude Portmann, and François Vernadat. A model for cooperative planning within a virtual enterprise. *International Journal of Computer Integrated Manufacturing*, 19(03):197–209, 2006.

Marco A Pego-Guerra, WJ Zhang, and WH Ip. Robust management of virtual enterprises. In *International Design Engineering Technical Conferences and Computers and Information in Engineering Conference*, volume 44144, pages 299–306, 2010.

Reyner Pérez-Campdesuñer, Gelmar García-Vidal, Alexander Sánchez-Rodríguez, Rodobaldo Martínez-Vivar, Margarita de Miguel-Guzmán, and Elizabeth Guilarte-Barinaga. Influence of the socio-economic environment on the entrepreneurs behavior. cases of cuba and ecuador. *International Journal of Engineering Business Management*, 13:1847979021994509, 2021.

Silvio RI Pires, Carlos F Bremer, Luis A De Santa Eulalia, and Christiane P Goulart. Supply chain and virtual enterprises: comparisons, migration and a case study. *International Journal of Logistics*, 4(3):297–311, 2001.

Marcos A Pisching, Fabrício Junqueira, Paulo E Miyagi, et al. Service composition in the cloud-based manufacturing focused on the industry 4.0. In *Doctoral Conference on Computing, Electrical and Industrial Systems*, pages 65–72. Springer, 2015.

Evelyn Paola Soto Rojas, Ana Cristina Barros, Américo Lopes de Azevedo, and Antonio Batocchio. Business model development for virtual enterprises. In *Working Conference on Virtual Enterprises*, pages 624–634. Springer, 2012.

David Romero, Ricardo J Rabelo, Mauricio Hincapie, and Arturo Molina. Next generation manufacturing systems and the virtual enterprise. *IFAC Proceedings Volumes*, 42(4):630–637, 2009.

Anna Paula Galvão Scheidegger, Tábata Fernandes Pereira, Mona Liza Moura de Oliveira, Amarnath Banerjee, and José Arnaldo Barra Montevechi. An introductory guide for hybrid simulation modelers on the primary simulation methods in industrial engineering identified through a systematic review of the literature. *Computers & Industrial Engineering*, 124: 474–492, 2018.

Markus Schwaninger and Peter Vrhovec. Supply system dynamics: distributed control in supply chains and networks. *Cybernetics and Systems*, 37(5):375–415, 2006.

Radim Špicar. System dynamics archetypes in capacity planning. *Procedia Engineering*, 69: 1350–1355, 2014.

John Sterman. *Business dynamics*. Irwin/McGraw-Hill c2000.., 2010.

Erma Suryani, Shuo-Yan Chou, Rudi Hartono, and Chih-Hsien Chen. Demand scenario analysis and planned capacity expansion: A system dynamics framework. *Simulation modelling practice and theory*, 18(6):732–751, 2010.

Wenan Tan, Yicheng Xu, Wei Xu, Lida Xu, Xianhua Zhao, Li Wang, and Liuliu Fu. A methodology toward manufacturing grid-based virtual enterprise operation platform. *Enterprise Information Systems*, 4(3):283–309, 2010.

Antônio Márcio Tavares Thomé, Luiz Felipe Scavarda, Nicole Suclla Fernandez, and Annibal José Scavarda. Sales and operations planning: A research synthesis. *International journal of production economics*, 138(1):1–13, 2012.

Andrew C Trapp, Renata A Konrad, Joseph Sarkis, and Amy Z Zeng. Closing the loop: Forging high-quality agile virtual enterprises in a reverse supply chain via solution portfolios. *Journal of the Operational Research Society*, 72(4):908–922, 2021.

Maliheh Vaez-Alaei, Ioana Deniaud, François Marmier, Didier Gourc, and Robin Cowan. A partner selection framework for strategic alliances based on project complexity and partner's past experience. *Enterprise Information Systems*, 16(6):1889038, 2022.

Rolando Vargas Vallejos, CP Lima, and Gregório Varvakis. Towards the development of a framework to create a virtual organisation breeding environment in the mould and die sector. *Journal of Intelligent Manufacturing*, 18(5):587–597, 2007.

Jayendran Venkateswaran and Young-Jun Son. Effect of information update frequency on the stability of production–inventory control systems. *International Journal of Production Economics*, 106(1):171–190, 2007.

François B Vernadat. Technical, semantic and organizational issues of enterprise interoperability and networking. *Annual Reviews in Control*, 34(1):139–144, 2010.

Wenming Xia and Guofu Li. Research on virtual enterprise production planning and control system. In *2008 Fourth International Conference on Natural Computation*, volume 6, pages 555–559. IEEE, 2008.

HY Yu, Akinola Ogbeyemi, WJ Lin, Jingyi He, Wei Sun, and WJ Zhang. A semantic model for enterprise application integration in the era of data explosion and globalisation. *Enterprise Information Systems*, pages 1–23, 2021.

Maximilian Zarte. Decision support system for production planning from a sustainability perspective. 2022.

Wen-Jun Zhang and Q Li. Information modelling for made-to-order virtual enterprise manufacturing systems. *Computer-Aided Design*, 31(10):611–619, 1999.

WJ Zhang and JW Wang. Design theory and methodology for enterprise systems, 2016.

WJ Zhang, X Liu, and CA Van Luttervelt. On the proposal of a new theory, methodology and computer aid for virtual enterprises manufacturing systems design-in relation to partner factories selection. In *Proceedings of International Conference of World Manufacturing Congress*, volume 97, pages 61–66. ICSC Interdisciplinary Research Auckland, 1997.