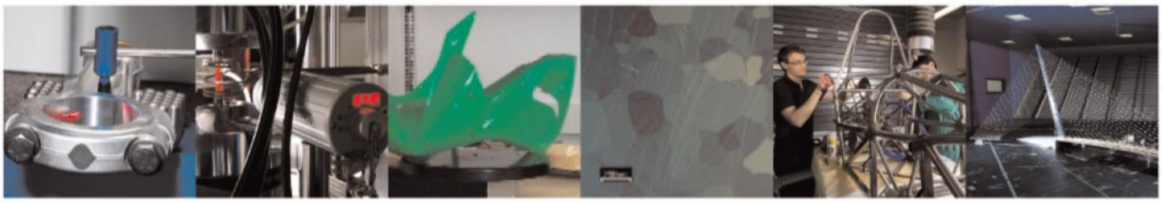

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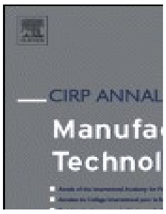

Hybrid digital modelling of large manufacturing systems to support continuous evolution

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Automation and technological innovations pushed manufacturing companies to integrated plant configurations, where sub-systems are highly intertwined, though easily reconfigurable thanks to modularization. Frequent reconfigurations change the way sub-systems interact among each other more often than in the past. However, in large manufacturing systems digital sub-system models may be still ran independently, limiting their support in decision-making. This work proposes a methodology for the hybrid digital modelling of large manufacturing systems, where hybrid stands for multi-technique modelling, to achieve: (i) reduction of modelling complexity, (ii) portability, (iii) optimal modelling choice, (iv) hybrid modelling integration. An industrial case study in the electrical equipment sector shows the validity of the proposed approach.

Keywords: Manufacturing system; Performance evaluation; Hybrid modelling.

1. Introduction

Automation and technological innovations have pushed manufacturing companies to have highly integrated plants: different production areas may use the same transportation system, off-line quality area may serve the whole plant, automated and partially automated assembly lines may take the raw material as input and return the final assembled product as output, covering the entire process chain. In this context, digitalization has supported the design and operations of manufacturing systems, so that now digital models can be considered as an industrial practice supporting the evaluation and analysis of reconfiguration and continuous improvement decisions [1]. Indeed, some technology suppliers start providing not only the physical machine, or system, but also its digital counterpart for controlling purposes. As a consequence, manufacturing systems have become large entities based on modular design of sub-systems, usually integrating multi-vendor technologies [2]. Frequent reconfigurations as machine replacement for technological innovations, re-routing due to novel operations management, capacity re-allocation for new product introduction continuously change the way sub-systems interact among each other, much more often than in the past [3]. However, when it comes to the corresponding digital model of the sub-systems, e.g. process machines, automated lines, job shops, the continuous updating of the digital models still requires much effort [4] and frequently is not performed due to the difficulty of integrating old and new models. As a result, within a large manufacturing system, there might exist several digital models, developed with different techniques, which are ran and used independently from each other [5] therefore even if the real system is integrated the digital counterpart of the system is not.

In recent years, the integration of multi-paradigm digital model has been used by researchers, i.e. *hybrid* modelling. On the one hand the reason is to exploit modelling functionalities which could not be considered otherwise, as in the integration of Discrete Event Simulation (DES) and System Dynamics [6], where one model is fully embedded within the other. Similarly, successful applications include the integration of DES with agent-based models for control evaluation purposes at shop-floor level [7]. Other examples include the use of known standards for distributed simulation of manufacturing systems [8]. In the aforementioned approaches, the focus is at entity level, which make these approaches suitable for short-term analysis and optimization, since their goal is the time synchronization of the different models. When medium-term problems are considered, as to the scope of the proposed work, most of the works in *hybrid* modelling do not need time synchronization among models. The areas of application include the integration of mathematical programming methods and evaluation models [9], where the latter provide performance approximations to search algorithms [10] and multi-scale modelling, where models with different level of fidelity are vertically integrated to evaluate performance at various scales and with different levels of approximations [11]. The method proposed in this article aims at the integration of models that represent different portions of the same system in the horizontal direction, i.e. according to the material flow.

An alternative to integrating different models would be to create a unique system model. Considering for instance Discrete Event Simulation (DES) models, the implementation and validation phases may take up to 45% of the total effort in a simulation project and this time increases with the complexity of the model itself. Complexity can be measured in many ways, as in [12], [13], i.e. as a function of the number of edges, nodes and connections of the corresponding system graph (as in neural network modelling), or as a function of the system *information entropy*, which depends on the existing system uncertainty, arguing that a more complex system has also more uncertainty [14]. Hence, digital modelling of large manufacturing systems is a complex and challenging task, due to the high number of resources involved, the huge amount of interconnections and inter-relations among them, and the existing uncertainty which may compromise the level of detail needed in the modelling [15]. Therefore, creating a unique big system model is impractical in most of the cases.

In this work, a general methodology for the hybrid digital modelling of large manufacturing systems is proposed, where hybrid stands for multi-technique modelling. The methodology grounds on the integration of sub-system models as building blocks by means of state based pseudo-representations of the sub-systems themselves. A decomposition method links each building block to estimate the joint relations among sub-systems and therefore to evaluate the performance of the overall large manufacturing system. The objectives of the proposed approach are manifold: (i) reduction of structural and information complexity of the developed models, thus reduction of model development and validation effort; (ii) easy portability and reconfiguration of digital models by means of modular design and implementation, thus enabling the correspondence of the evolution between the digital model and its real counterpart; (iii) usage of the best modelling option according to available information, (e.g. analytical models for fast evaluation of defined production system architectures, meta-models based on machine learning for data-rich systems, simulation models for systems where other modelling options cannot be used); (iv) integration of already existing models or of black-box models, to avoid model overlapping or replication.

2. Methods

2.1. Concept of decomposition in large manufacturing systems

In large manufacturing systems, as the one depicted in Fig. 1a, where squares represent stations and circles represent buffers, sub-systems may be identified as sub-portions of the whole manufacturing system. Each sub-portion can be identified as a different production system performing a set of operations on the products, e.g. machining, assembly, packaging.

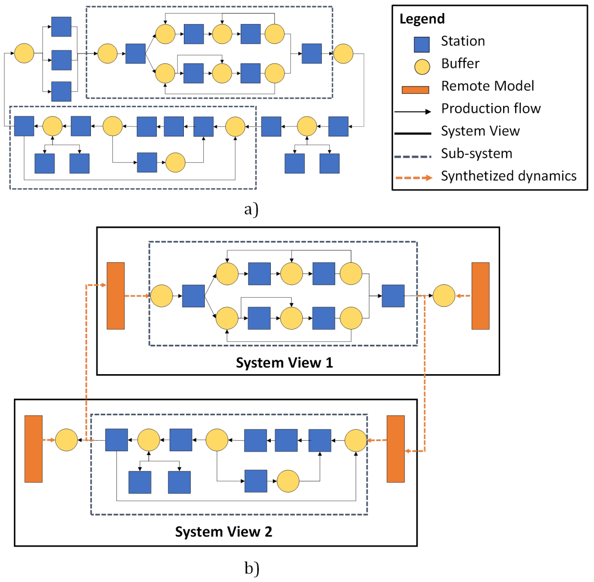


Figure 1. Decomposition of large manufacturing systems (a) in System Views (b).

The proposed method is based on “System Views”, which are different models of the same large system each centred on a specific subsystem, as those represented in Fig. 1b. System Views may be created using different modelling paradigms (e.g simulation, analytical tools, surrogate models) and include a detailed model of the sub-system and Remote Models. Remote Models are a synthetic and state based representation of the other sub-systems of the large manufacturing system other than the one detailed in the view. Within each view the behaviour of the whole system can be estimated from the interaction between detailed model and Remote Models. Coherence among the different system views is obtained as follows. Within a specific view, Remote Models are used to represent the limitations and dynamics that other portions of the large system exercise on the detailed model at the centre of the view. In turn, the sub-system under analysis is introducing limitations to the other sub-systems. These limitations are synthetized in the Remote Models in the other views. The number of Remote Models needed for each view depends on the number of other sub-systems that are directly connected with the considered one. Therefore, each sub-system is represented in multiple ways in the different views. In one view a detailed representation is given, in another a synthetic representation is used. Since all the representations refer to the same sub-system they must be coherent. This is considered in the creation of the Remote Models. In the following, the characterization of Remote Models is provided; then the numerical algorithm used to obtain the large system evaluation is described.

2.2. Characterization of Remote Models

In a given System View, by considering a specific machine in the detailed model, it is possible to observe the behaviour depicted in Fig. 2, where 1 indicates that the machine is currently delivering parts, and 0 indicates that the machine is currently not delivering parts.

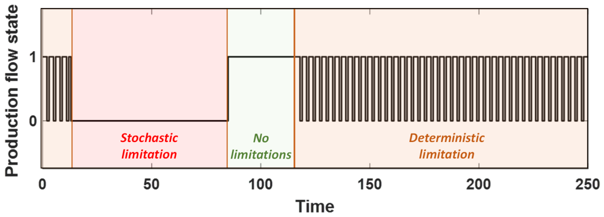


Figure 2. Sample-path of the production flow state with highlighted limitations.

It is possible to notice periods of no limitation and periods of stochastic limitations and deterministic limitations [16]. Deterministic (or quasi-deterministic) limitations are generated by the interaction among asynchronous automated machines, due to the fact that faster machines should wait for the slow ones to complete the parts, while being operational. This occurs when upstream inter-operational buffers are empty, or downstream inter-operational buffers are full (therefore the machine behaviour is coupled with the one of a neighbouring machine). A system tends to stay in these production cycles most of the time, since generally automated manufacturing systems are quite efficient. On the other hand, stochastic disruptions may occur, such as failures, breakages, which prevent the production flow to be delivered in certain periods (stochastic limitations). Normally those periods are followed by transient periods of no limitations in which buffers become empty or full before going back to deterministic limitations. If the machine under analysis is at the border of the detailed model (System View 1 of Fig. 1b) it interacts with a set of machines of the detailed model and with a Remote Model. Its behaviour will still be of the type described above, however some of the limitations will be due to the Remote Model. At the same time the machine under analysis limits the behaviour of the Remote model. Considering now the other view (System View 2 of Fig. 1b) the machine under analysis becomes part of the Remote Model. Therefore, its production flow represented in Fig. 2 must be replicated but in a synthetized way. The synthetic representation is a state based model (Fig. 3) in which the possible states of the production flow are considered together with the transitions among them. Normally there is one state in which the production flow is active and many states representing the different causes that prevent production flow. The production flow is determined by the transitions among the states. Therefore, in order to create the Remote Model there is the need to define the characteristics of these transitions. In deterministic transitions the time the production flow spends in

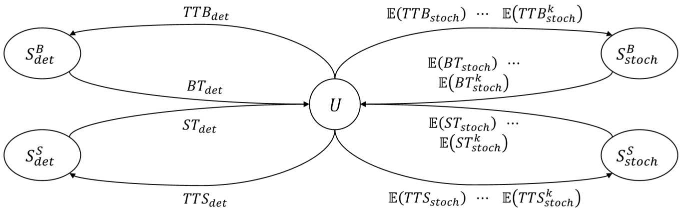


Figure 3. State based representation of the Remote Model

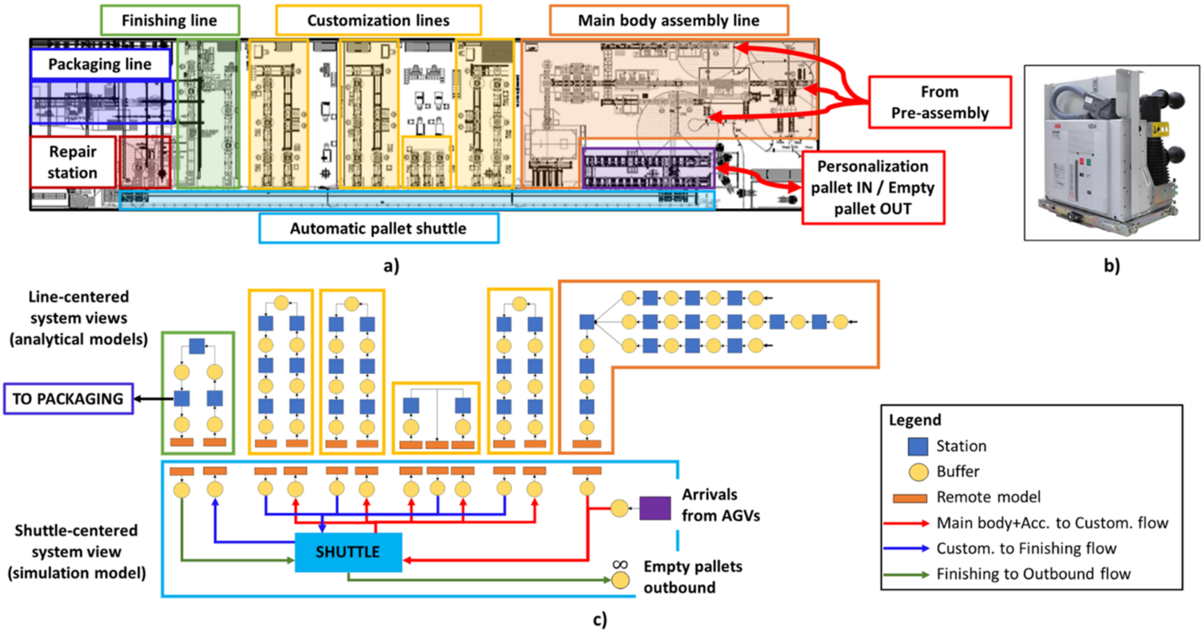


Figure 4. (a) Layout of the production system (courtesy of ABB SpA). (b) A circuit braker. (c) Schematization of the hybrid model.

each state is deterministic and therefore is represented by specific numbers. In the stochastic transitions (failures, repairs) the time spent in the various states is stochastic and must be represented by appropriate distributions. In the proposed model, distributions are characterized by means of the first k moments. Therefore, this gives the ability to the modeller to select the proper level of fidelity of Remote Models according to the needs, by increasing or decreasing the number of states and moments.

As it can be noticed, three sets of states are used:

- *U:* operational state, where the sub-system is delivering parts at its nominal rate.
- S^{B}_{det} and S^{S}_{det}: sets of states modelling the deterministic limitations of blocking or starvation type. These states are characterized by transitions estimated according to the operational cycles of the sub-system (TTB_{det}, BT_{det}, TTS_{det}, ST_{det}).
- S^{B}_{stoch} and S^{S}_{stoch}: sets of states modelling the stochastic blocking or starvation disruptions. These states are characterized by transitions obtained according to the k moments of the Time to Blocking and Blocking time, and Time to Starvation and Starvation time respectively ($\mathbb{E}(TTB_{stoch}), \ldots, \mathbb{E}(TTB^{k}_{stoch})$).

The parameters characterizing the transitions of the Remote Model are calculated by observing the behaviour of the detailed model at its border. Since only the behaviour at the border of the detailed models is required to create the Remote Model, the method works even in cases the detailed model is a black box (e.g. an existing simulator or a model which cannot be opened because created by other entities.

2.3 Decomposition algorithm for hybrid evaluation

The goal of the decomposition algorithm is to numerically characterize the Remote Models in order to fully describe the System Views. The selected algorithm is based on the one proposed in [17], and herewith further generalized, as in Table 1.

Table 1. Algorithm for the hybrid modelling

```
Algorithm: Decomposition algorithm for hybrid modelling
  iteration = 0;
  Step 0 For n = 1...N, System Views SV(n) and Remote Models RM(n) are initialized. Throughput TH(n) of each sub-system is computed.
while max TH(n)- min TH(n)<ε
iteration = iteration+1
Step 1 For n = 1...N:
1. System View SV(n) is executed; output is computed: (i) throughput TH(n); (ii) k moments of starvation distribution; (iii) operational cycle.
2. Remote Model RM(n+1) is characterized with (starvation) stochastic limitations and deterministic limitations.
Step 2 For n = N...1:
1. System View(n) is executed; output is computed: (i) throughput TH(n); (ii) k moments of blocking distribution; (iii) operational cycle.
2. Remote Model RM(n-1) is characterized with (blocking) stochastic limitations and deterministic limitations.
end
```

At the end of the proposed algorithm, all System Views will be characterized by the same throughput *TH*, hence ensuring the conservation of flow. Moreover, the state probabilities of Remote Models indicate the overall limitations for the considered sub-system. Hence, the saturation of each sub-system can be computed as: *Saturation = Prob(U)*.

3. Case study: production of medium voltage circuit brakers

3.1. Description of the large manufacturing system

The proposed method has been applied to a manufacturing system for assembly of medium voltage circuit brakers (Fig. 4b). The system produces four main products: three models of vacuum circuit brakers and one model of gas circuit braker. Each model is produced in two versions: withdrawable and fixed. Each circuit braker can be customized in some components (cabling, coils, contacts) to meet the specific requirements of customers. Fig. 4a shows the layout of the system. The pre-assembled structure of the switch arrives to the *Main body assembly line*, where the main mechanical components are assembled, and tests are performed. In the meanwhile, pallets with customization accessories are brought by AGVs to a dedicated conveyor. Main body and accessories are then transferred to one of the *Customization lines* by means of a railed automatic pallet shuttle, depending on the switch version: three lines are dedicated to withdrawable switches and two parallel stations are dedicated to fixed switches. After customization, the pallet shuttle transfers the switch to the *Finishing line*, where final assembly and testing are performed. At the end-of-line testing station, one operator removes the finished switch from the pallet and places it on the testing machine. After the test is completed, the operator transfers the switch to the *Packaging line*, while the pallet shuttle transfers the empty pallet to an outbound conveyor where it is picked by AGVs and operators. A *Repair station* is devoted to major repairs and corrections, while minor defects are fixed at assembly stations.

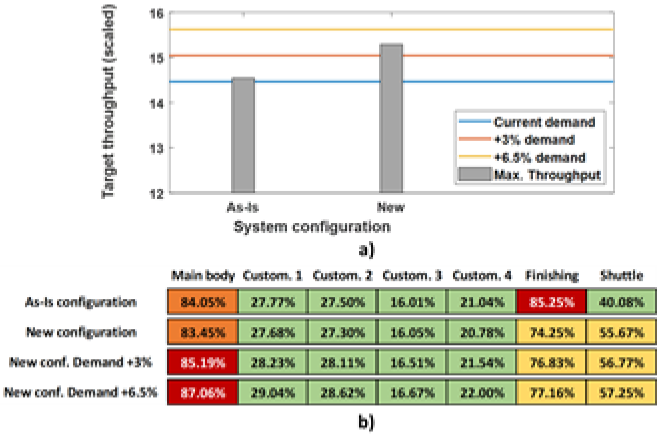
3.2 Modelling and analysis of results

In such a large manufacturing system, capacity planning represents a strategic task for the production manager [18], which is highly intertwined with improvement planning decisions. The described manufacturing system has undergone various changes to address, on one hand, the need for increased production efficiency by means of technological innovations, on the other hand, changes in the product mix as well as in the overall demand.

In this context, the hybrid modelling method has been used to evaluate the system capability of satisfying the demand under different configurations and for varying production scenarios.

Seven sub-systems can be identified, leading to seven System Views, each containing the detailed model of the corresponding sub-system and Remote Models, as depicted in Fig. 4c. The System View centred on the pallet shuttle is modelled with DES, while analytical models are used for System Views centred on assembly lines. All models have been fitted from production data. The advantages of the proposed approach have been clear when it was possible to (i) parallelize the modelling activities, hence reaching the final model in a relatively short time; (ii) use the most suitable modelling paradigms according to system requirements, thus reducing the modelling and validation effort; (iii) reduce the overall model complexity with respect to the update, modification, replacement and enhancement of each sub-system model.

Indeed, due to increasing demand, the final part of the line, i.e. the Finishing sub-system, started suffering high saturation levels (more than 85%). The hybrid approach allowed also to quantify the saturation of other sub-systems, as illustrated in Fig. 5b, showing that also the other side of the large manufacturing system, i.e. the Main body line, was approaching a critical saturation level.



	Main body	Custom. 1	Custom. 2	Custom. 3	Custom. 4	Finishing	Shuttle
As-is configuration	84.05%	27.77%	27.50%	16.01%	21.04%	85.25%	40.08%
New configuration	83.45%	27.68%	27.30%	16.05%	20.78%	74.25%	55.67%
New conf. Demand +3%	85.19%	28.23%	28.11%	16.51%	21.54%	76.83%	56.77%
New conf. Demand +6.5%	87.06%	29.04%	28.62%	16.67%	22.00%	77.16%	57.25%

Figure 5. System throughput (a) and sub-systems saturation (b) for different configuration and demand scenarios.

Therefore, it was decided to reduce the pressure on these systems. In particular, testing and transport operations were decoupled by adding a new downstream conveyor, served by the shuttle, where an operator transfers the switch to packaging (new configuration). In this way, the production rate at the critical stations was increased in order to reduce blocking limitations. Although this has the positive effect of decreasing the saturation where expected (from 85.25% to 74.25% at the Finishing), it also increases the Shuttle saturation (from 40% to 55.67%). Finally, considering the demand trend, the configurations have been tested also for increases of 3% and 6.5%. While in the first case the new configuration can satisfy the demand (red line in Fig. 5b), in the latter case the target throughput cannot be reached (yellow line), leading to a highly saturated Main body sub-system, and slight increase in the saturation of Finishing and Shuttle. Further analysis are being conducted with the company, focusing on the Main body line, to evaluate the possibility of introducing new machines or replacing old ones, as well as reallocating the workforce, while taking into account constraints that are currently present in the company.

4. Conclusions and future work

This work introduces a general methodology for the hybrid digital modelling of large manufacturing systems. The advantages include the reduction of complexity of the models, as well as the portability of digital models to support the continuous evolution of manufacturing systems. This is achieved by encoding the joint limitations and effects among sub-systems into a set of different representations of the whole manufacturing system characterized by alternative level of details. By doing so, the update, replacement or integration of multi-technique digital models, as DES, analytical, meta-models is made possible.

In this way, digital models can support the continuous evolution of manufacturing systems by fully adhering and keeping the pace with the frequent reconfigurations and modifications which may occur during the plant lifecycle. Future research will regard criteria for the selection of the optimal number of sub-models considering complexity and computational effort, generalization of the proposed approach to ease plug-in modelling methodologies in the hybrid evaluation, as well as analysis of large optimization problems where the understanding of the system operations is needed.

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