A Methodology for the Development of Interoperable BIM-based Cyber-Physical Systems

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Abstract –

Building Information Modeling (BIM)-based processes are increasingly being adopted worldwide. With it, possibilities to exploit digitization had been appearing for the AEC sector. In that context, the present work aims to investigate how, and in which form, a Cyber-Physical System (CPS), one of many different but complementary technologies associated with the future of manufacturing, could be employed in the Construction industry. Recognizing that the core of CPS should be the dynamics of construction processes, the initial focus is in how to develop Process Data Models (virtual) that could communicate with Product Data Models (BIM models), and receive/send data in almost real-time from/for the existent hardware (sensors and actuators) in the physical production processes. This article present some preliminary work based on the standardized methodology of IDM/MVD, which are part of the buildingSMART solution for interoperability along with Industry Foundation Class (IFC) data schema. The proposed methodology considers an IDM modelled in Business Process Modeling and Notation (BPMN) language in such detail as to expose the workflow of production. The contribution in this context is in mapping production processes in BPMN notation into Petri Nets (PN) semantics. Petri Nets are an adequate model to construction processes, with precise semantics and largely used in the simulation of discrete events. With PN models it would be possible to develop the BIM-based control strategy, and test and implement it in real controllers. An illustrative example is provided in the context of automating cut and bend of rebar.

Keywords –

Cyber-physical systems; IDM-MVD; Construction Simulation; BIM

1 Introduction

Building Information Modeling (BIM)-based processes are increasingly being adopted worldwide. It could be viewed as the digitization phenomena that allows further adoption of technologies related to the automation and employment of robots in the Construction industry [1].

However, BIM models, with probably rare exceptions, are in reality Product Data Models [2]. For the effective introduction of automation technologies, it would be necessary to have, explicitly, Process Data Models [3]. Automated Construction [4], in its core, should be about control systems for production processes. Advanced applications of automation and robotics in construction already emphasized this notion [5].

In that context, the present work aims to investigate how, and in which form, a Cyber-Physical Systems (CPS) could be employed in Construction. A CPS could be viewed as a control system, which integrates the cyber world of computational models of products, process, organization behind production, supply-chain, and so on, with the physical world of sensors monitoring material, equipment, manual labor, machines and robots, and its actuators. It is a complex field of research that is in its infancy.

Towards a viable development of such a CPS, it would be economical to adopt open standards and current industry practices. Industry Foundation Class (IFC), both a data schema and a file format to exchange building information of its entire lifecycle, is becoming a *de facto* open standard for the interoperability in the aforementioned processes.

The focus is in how one could develop, in the interoperable scenario proposed by buildingSMART, a process (virtual) model that could communicate with Product Data Model (BIM models) and the hardware/software in the production processes.

This article present some preliminary work based on the standardized methodology of IDM/MVD, which are part of the buildingSMART standards, and are used to specify a subset of IFC entities. First, an IDM should be modelled in Business Process Modeling and Notation (BPMN) language, in such detail as to expose the workflow of the production process. Then a map between BPMN and Petri Nets, an adequate model to construction process with precise semantics and used in simulation of discrete events [6], is applied providing the basis for implementing a CPS.

An example is provided in the context of automating cut and bend of rebar.

2 Cyber-Physical Systems in Construction

Cyber-Physical Systems (CPS) is probably one of the most important technology associated with the current Industry 4.0 paradigm for manufacturing, because it is the integration of many of them. Implementations of such systems are already happening in the manufacture industry, mostly in automotive and aerospace.

One way to see it, is that it enables the integration between the virtual world (digital models and simulations) with the physical world (by means of sensors – Internet of Things/Industrial Internet – and actuators – Automation equipment and robots). The necessity of integration between different systems, or islands of automation, is not new.

Depending on the way cyber-physical system is defined or approached, one could find many or few research articles in the literature. If bidirectional data transfer between computational platforms with virtual models of construction and the construction field is sufficient to have an effective CPS, there is plenty of works dealing with monitoring the work done on site with different sensors [7]. However, to consider that it is necessary to have an actuator receiving commands to control some equipment on-site, it is hard to find one approach that integrate automated equipment with BIM models. Considering the evolution of the employment of robots on the field [8], it would be interesting to study the impact of CPS system in this context.

In [9], two scenarios are proposed that could employ CPS in Construction, based on the view that a CPS is a bidirectional data transfer: steel placement and light fixture monitoring and control.

In this article, it is considered that a CPS could be viewed throughout one spectrum of possibilities, which could become more functional or important as it integrates more technologies, such as sensors, automated equipment/robots, data analytics, simulation of construction process, and so on.

However, it is advocated that independently of the level of development of the CPS, the essential point for the integration is the virtual model of the different construction processes, in which it would be the bi-directional link. Henceforth, the necessity to study how to represent the knowledge of construction processes inside BIM platforms.

3 Construction Simulation with Petri Nets

It is important to note that BIM models are Data Product Models. Analyzing IFC Schema, although it is possible to instantiate processes, there are not standard construction processes already present in the schema, as are the building components used to design and construct a building.

Some author emphasize the difference and necessity of product and process model [2]. Mostly, the referred authors calls that approach Virtual Design and Construction (VDC), although the process model adopted many times are not a computational model.

To have the ability to simulate, analyze, and optimize production processes are the main drive for the importance of the process digital model. And as the simulation will be the core of a CPS, the kind of digital model should have characteristic appropriated for control systems.

Petri Nets were considered adequate to model and simulate construction processes, which presents a high degree of concurrency and synchronization.

A Petri Net is a tuple, given by [10]:

$$N = (P, T, \mathrm{E}) \quad \textbf{(1)}$$

where: P is a finite set of places; T is finite set of transitions; and E is the incident relation, representing the set of directed arcs connecting places to transitions and vice-versa, given by:

$$\mathrm{E} \subseteq (P \times T) \cup (T \times P) \quad \textbf{(2)}$$

There is also a token, a mark inside places, to represent the dynamics of the net. One transitions only occurs if there are token in every place connected to it. And if a place is connected to two transitions, and both could fire, a decision should be made.

3.1 Types of Petri Nets

There are many different formalisms to define Petri Nets with added capabilities: *Colored Petri Nets* [11], *Hierarchical Petri Net* [12], *Controllable Petri Nets* [13], and on. It is not the objective of this work, in this initial research, to define which one is more adequate to the cyber-physical system in hand, at that time. It will be considered in the following discussion a regular Petri Net.

Construction Processes would be experimented with **untimed models** with Petri Nets, as there exists an order in the events that occurs for the production of building components. Where there will be necessity to develop the control of the manufacturing process, it will be the **Control Theoretic Approach**, where there is a "model of the plant dynamics and a specification for the desired closed-loop behavior". "There is a clear distinction between the plant and the controller and the information flow between the plant and controller is modeled explicitly" [10].

The main problem would be to create such Petri Net based on construction information, inside the current practices present in BIM implementations

4 Interoperability with IFC: IDM/MVD Methodology

Industry Foundation Classes (IFC) are both a schema for the entities of the products of the AEC industry and a file format to exchange those data product models. It comprises the entire lifecycle of a building.

The main concern with working with IFC is its complexity and size. buildingSMART is the international organization behind the efforts to promote open-BIM. As a building traditionally is represented by a set of BIM models, one for each discipline, those models are used in exchanges between different professionals to promote cooperation and concurrent work.

In each exchange, only part of a given model is needed. buildingSMART have being promoting the methodology of creating different Model View Definitions (MVD), that are a pre-defined subset of the IFC Schema, with agreed representation for the allowed entities.

However, there are few MVDs available, and this is part of the misconception that IFC do not work out-of-the-box in practice. Software vendors are certified as IFC exporters based on Coordinating View exchange (one MVD), which is not appropriate, for instance, for energy analysis.

Part of the cause for the existence of few MVDs is difficulty of the process of creating one and making it official at buildingSMART [14]. The methodology consist in first creating an Information Delivery Manual (IDM), basically a diagram in BPMN (Business Process Modeling Notation) notation, which all professionals could understand, and based on that, translate each piece of information, based on MVD Concepts.

Considering this scenario, where the different professionals involved in Construction are more comfortable in developing models using a language such as BPMN than Petri Nets, in this article it is proposed that a map between both models should be a solution for that.

As IDM is a high-level representation of a construction process, it should be exploited in the open-BIM scenario to produce process models.

5 Proposed Approach for CPS in Construction

The end of the spectrum of possibilities (most advanced) of CPS in Construction, should consist in a scenario with automated or semi-automated fabrication, with employment of machines or robots – as is currently more common in off-site production.

However, the proposed approach of this article contemplates a modular solution, around BIM models:

- A module for the simulation of construction processes in the form of a Petri Net (built upon the respective IDM diagrams) – which is considered here to be core of the CPS;
- A module for monitoring the construction processes, using whichever sensor (RFID, Ultrawide-band, laser scanners, Images, and so on). It feeds the CPS (or the platform using BIM models) with (possibly, real-time) data;
- A module for (Big) Data Analytics, based on the dynamics of the construction process and the BIM Models;
- A module for automatic decision-making routines, given to construct management personnel, or, direct control commands to machines in on- and off-site.

In that way, it aims to provide an enhancement of the employment, and existence of BIM implementations. Its most distinct characteristic is to associate the **process data model** with a CPS system, which connects and integrate with other technologies used by the enterprise.

In its simpler incarnation, it would be a way to monitor, with the capabilities of each sensor employed, what really happens on-site (off-site), so that it could be used as data to act more quickly to solve problems, and to study ways of optimization of the processes.

5.1 CPS: From IDM to Petri Nets

The idea is not new; neither was it developed by the present authors. However, upon finding previous work [15] on the subject, BPMN mapping in Petri Nets, it was considered a matter of investigation of its adequacy, in a scenario where some construction processes are currently being modelled in BPMN, and it is a language more closer to the background of the team of professionals involved in Construction industry.

IDMs are currently created using BPMN language [16]. The main problem with BPMN is that it inherits and combine constructs from different graph-oriented process definition languages with other features, drawn from a range of sources [15], and could produce semantic errors. Mapping it in Petri Nets allows the verification of its consistency. However, the main interest of Petri Nets for the proposed approach is that it is largely used to model and control manufacturing processes.

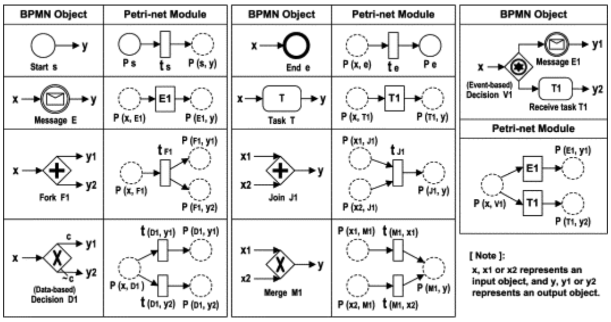

Figure 1. List of symbols considered and mapped into Petri Net constructs [15].

In [15], the authors provided a mapping between BPMN notation and Petri Net, which is adopted in this work as is (Figure 1). A subset of symbols from BPMN notation were considered, and it is compatible with symbols used for the IDM / MVD specification [16].

5.2 Example: Process for Automated Cut and Bend of Reinforcing Bars

5.2.1 IDM / MVD for Automated Cut and Bend of Reinforcing Bars

As the authors of the present article are working in the development of a IDM / MVD for the automated cut and bend of reinforcing bars as a BIM process [17][18], it was decided to use this scenario to illustrate the mapping between IDM (BPMN) to Petri Nets (Figure 2).

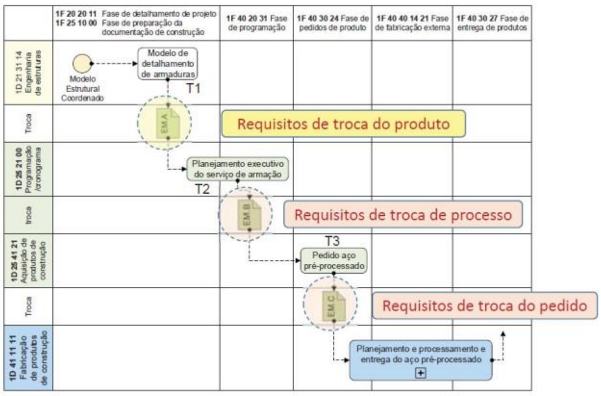

Figure 2. Example of an IDM in BPMN language for the Automatic Cut and Bent of rebars.

The IDM is the business process in BPMN notation. It contemplates 5 phases (Design Detailing and Preparation of Construction Documents; Programming; Product Orders; External Fabrication; and Product Delivery) and 4 disciplines (Structural Engineering; Schedule Programming; Acquisition of Construction Product; and Fabrication of Construction Product), following codes from NBR 15.965 (a Brazilian standard, based on Omniclass). In addition, it represents three exchange requirements: T1 (product), T2 (process), and T3 (order).

The level of detail achieved (and it is that way throughout this development in Construction industry) in modelling IDM for MVD specification is not enough for it be immediately mapped (and be relevant) in a Petri Nets, as it do not exposes detail of the fabrication process.

5.2.2 Sub-process: Fabrication of Reinforcing Bars

In the industrial process of cut and bend of reinforcing bars (rebars), there is a team dealing with orders received (containing delivery date and reference drawings for rebars processing). This team does a preliminary analysis of the order (reference drawings missing, errors in data filling in the forms), and contacts the client if necessary. If everything is correct, the next stage is to send forward the orders and the reference drawings (Rebar Detailing Project) to the scheduling team, which will transcript design data to production (geometry and quantities of each bend format). That information is entered in the production management software of the service (cut and bend) provider.

In the sequence, the Production Planning and Control starts. In general, large cut & bend providers have many equipment working simultaneously. Each equipment works with a specific diameter of steel bars, and have restrictions of bend shape that it could process (for example, maximum length of the bar to be bend).

Also, a pool of orders is stablished to achieve a given volume of production, to keep the line operating continuously, and to make some optimization in reducing possible lengths of lost from the raw material [19].

5.2.3 BMPN diagram of the fabrication process

For this example, it will be considered just one machine operating, starting from the point where the previous dynamic description ends. There are different types of machines that produces reinforcing bars [20], and here it will be considered types A or B machines (Figure 3).

Figure 3. Schnell's A type machine.

Therefore, it was developed a prototype of a sub-process for the task that appears in blue in Figure 2, with the right amount of detail, to provide a BPMN notation (Figure 4). The model considers orders arriving in regular intervals. Given the availability of appropriate reinforcing bars (same diameter and material as ordered), the processing of rebars remains active due to place rebars_batch.

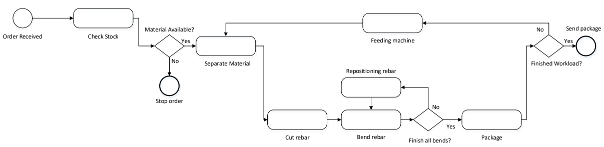

Figure 4. Sub-process for the fabrication of reinforcing rebars.

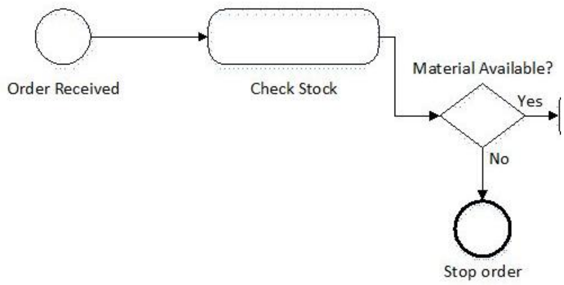

Figure 5. Initial part of the BPMN for Automated Cut and Bend of Rebars.

In the sequence (Figure 5), an order received (*Order Received*) is the start of the modelled process. The task *Check Stock* check if the material to attend the arrived order is available in the stock. Then, a gateway divides the flow: is there is material, then order follows along the path; if not, that is the end of the process (*Stop order*).

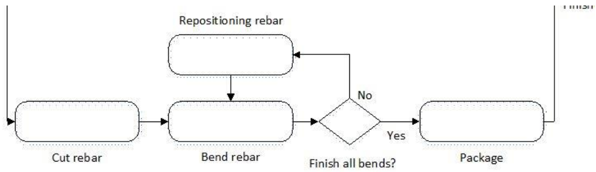

Figure 6. The part of the process were the rebars are cut and bend, following specification in BIM model.

After the gateway, there is a task (which is not represented in Figure 6) called *Separate Material*, in which the raw bars from the specified material are separated and brought closer to the machine. Then happens the tasks *Cut rebar* and *Bend rebar*. As could be more than one bend for each rebar, there is another gateway to check if all bends for that rebar were done (*Finish all bends*). If not, there is a task named Repositioning rebar, as an operator sometimes exist to conduct the positioning and gives command to the machine make another bend. When all bends were done, the flows goes to the *Package* Task.

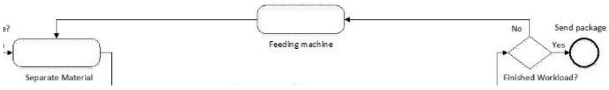

Figure 7. Final loop to produce all rebars of a given order.

From *Package* task, there is a final gateway (Figure 7) that checks if all rebars of the given order were produced. If yes, then the flows and the process ends at *Send Package* (end node). If not, it goes to the task *Feeding machine* and then again to *Separate Material*, and the process of cut and bend of the rebar starts again in another rebar, which were previously separated.

5.2.4 Mapped Petri Net

Applying to this model the map presented in Figure 1, the Petri Net represented in Figure 8 is obtained.

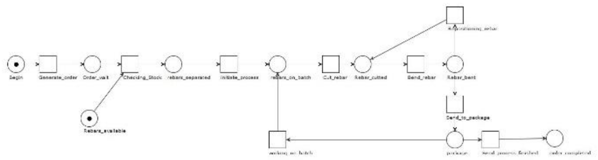

Figure 8. Petri net derived from BPMN subprocess.

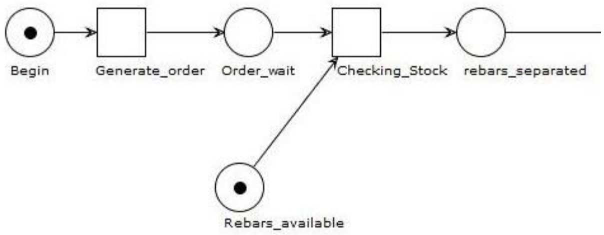

Figure 9. Initial part of the Petri Net mapped from BPMN diagram.

The token are added from simulate the dynamics of the net: one token to start the process (*Begin*), as an order arriving, and one at place *Rebars_available* (Figure 9).

The transition *Generate_order* is active and fires. Token moves to *Order_wait* place. The transition Checking_Stock become active, as there are tokens in both predecessor places (*Order_wait* and *Rebars_available*), and the token moves to *rebars_separated*. Note that the net will not work again, even with the arrival of another order, because rebars_available must also receive another token. The connection of this process with other dependent was not modelled.

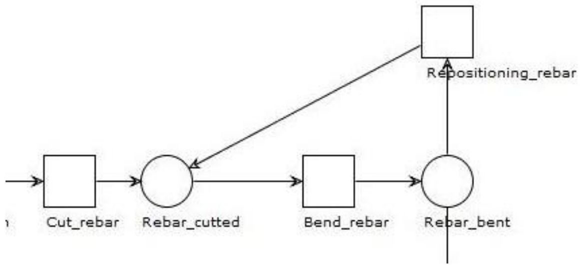

Figure 10. The cut and bend activities represented in the Petri Net.

Figure 10 do not show that after the place *rebars_separated* there are a transition *intiate_process*. After it, there is a place (that also not appears in the above figure) called *rebars_on_batch*. The token in this last place, activate the transition *Cut_rebar*, flows to *Rebar_cutted*, and then fires *Bend_rebar*, ending in the place *Rebar_bent*.

In the place *Rebar_bent* there is the possibility for two transitions to occur: *Repositioning_rebar*, if there are more bend to be made in the rebar, or *Send_to_package*, if this rebar is finished. If it is not finished, the transition *Repositioning_rebar* is activated and the token goes back to *Rebar_cutted*.

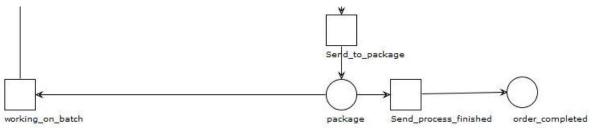

Figure 11. End of the process.

Figure 11 starts with the fire of transition *Send_to_package*, when all bend are made at the rebar. The token at *package* activates both *Send_process_finished* (if all rebars on the order were fabricated) and *working_on_batch* (if there still rebars to be fabricated). If the last transition is fired, it returns to place *rebars_on_batch*, and initiate again the cut and bend dynamics. If all work on that order is done, it fires Send_process_finished and goes to *order_completed*, with the simulation ended.

6 Results

In order to, somehow, validate the mapping (beyond test its dynamics in a software), one Petri Net was elaborated beforehand, and its dynamics tested with WoPeD (Workflow Petri Net Designer). The modelled Petri Net is represented in Figure 12.

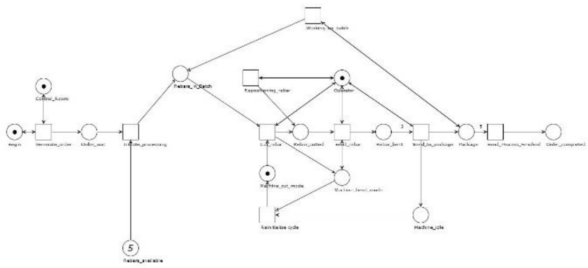

Figure 12. A previously modelled Petri Net for the same purposes.

Figure 13 represents the initial part of the process, with orders arriving; this part of the model was taken from the simulation presented at [21].

Figure 14 shows the cut and bend process of each reinforcing bar. First, the machine is in cut mode, and the operator is available. Then, the machine changes to bend_mode, and the operator makes the repositioning of rebars for further bends, until the number of bends are completed. The machine goes to idle state, and then back to cut mode.

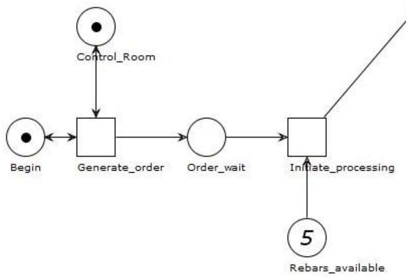

Figure 13. Petri net model for automatic rebar cut and bend (this part of the net is inspired by [21]).

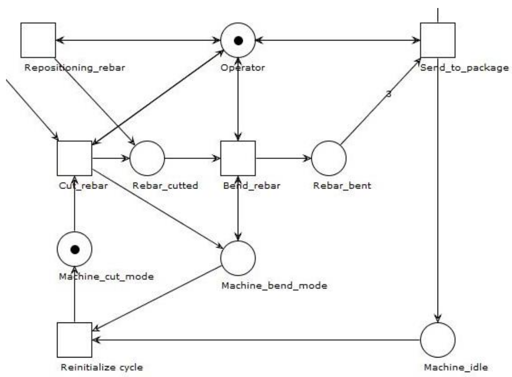

Figure 14. Processing of reinforcing bars.

At the same time, the first piece of the order, remains in the package, and maintain the rebar supply available to process new rebars in the same batch (Figure 15). The transition send_finish_process has precedence and stops further processing. The loop initiate again with a new order.

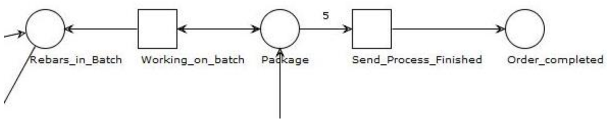

Figure 15. Final part of the model.

It is interestingly that where modelling the same process in BPMN, many details, such as the existence of an operator, and the difference in the type of machine (using one for bend and other for cut), are abstracted generating a simpler and functional network.

7 Conclusion and Future Works

This paper proposed the use of IDM/MVD workflow to start the development of a process model in Petri Net formalism. The objective in creating such model is that it could integrate information from BIM models and sensors and actuators signals for the plant process, obtaining a kind of cyber-physical system. This area is very promising, but the results are still preliminary.

The experiment of developing a simulation of construction processes as the core of a cyber-physical system was presented.

The focus of the article was in testing the relevance in using available IDMs, elaborated for BIM processes purposes, to produce one representation, Petri Nets, that allows to test its dynamics, and even its control strategy.

Initial results, were positive, as the mapping between IDM (in BPMN notation) produced Petri Nets more simple and functional when compared with a previous Petri Net elaborated from zero.

Another result is that the level of detail present in current IDMs ([14] was also analysed) is not sufficient for the proposed approach. But it is not difficult to proceed in the same notation to model sub-task or sub-activities to expose details of the fabrication processes.

Finally, a workable dynamic model in Petri Net probably needs more characteristics than BPMN could model. It should be considered a starting point to further develop to include controlled process, or a controller explicitly.

Interestingly, to produce from zero a Petri Net for this fabrication process, the resultant net was more complex, because many more details were inserted in its elaboration (and it was an iterative process) to achieve the right dynamics in the Petri Nets. When modelling with BPMN, it was easier to achieve a diagram that was translated in a simpler Petri Net, with about the same dynamics.

In the end, there was not necessary to deal with orders that necessitate different number of bends, or work packages with different number of rebars. In the mapped solution, this aspects was abstracted of the net, although it has the same dynamics.

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