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# 2MTO, a new mapping tool to achieve lean benefits in High-Variety Low-Volume job shops

## 1 Introduction

Lean manufacturing is one of the best ways to boost operational performances through a continuous removal of waste (Slomp et al., 2009). Nowadays, successful lean implementations are very common, not only in manufacturing, but also in services and supply chain management (Bonaccorsi et al., 2011; Jasti and Kodali 2015). Nonetheless, a fool proof way for lean implementation has not been developed yet and, probably, a general framework is not even conceivable (Braglia et al., 2009). Indeed, lean initiatives are case specific and high-level lean principles must be tailored to the specific circumstance under analysis. In this regard, within the manufacturing sector, researchers agree that adopting lean in Make-To-Order (MTO) job-shops would be beneficial, but very challenging (Parthanadee and Buddhakulsomsiri 2012; Romagnoli 2015; Slomp et al. 2009). These manufacturing environments, in fact, are characterized by High-Variety and Low-Volume (HVLV), features that are not ideal for a straight application of traditional lean tools (Haider and Mirza 2015; Marolla et al., In Press). This issue is also reflected by the scarcity of scientific works that focus on lean in MTO job-shops (Wiendhal 1995). Only a few papers can be found and, among the most significant ones, we can cite the works by Alves et al. (2005) and by Tham et al. (2007) that describe, respectively, lean projects in a job-shop facility of heat ventilation and air conditioning and in a high precision machining shop. Other interesting applications can be found in the works by Esfandyari et al. (2011) and by Gurumurthy and Kodali (2011) that combined Value Stream Mapping (VSM) and discrete event simulation, to optimize lean benefits in two job-shops located, respectively, in India and Malaysia.

However, all the above-mentioned papers have a common limit, as their analysis focuses, exclusively, on a single product family. In doing so, job-shops are assimilated to standard flow-shops, and alternative routings and/or machines' sharing are not properly considered. In our opinion, this mono-dimensional approach is myopic, as it ignores the raison d'être of a HVLV job-shop, that is its flexibility and its capability to manufacture different products on the same shop floor through alternative routings.

As an alternative approach, some authors proposed using hybrid Production Planning and Control (PPC) systems (Bertolini et al. 2016; Hopp and Spearman 2004), such as Constant Work In Process (CONWIP) and Workload Control (WLC). These systems are very promising and make it possible to achieve lean benefits also in MTO companies, as demonstrated by Thürer et al. (2012). However, WLC is almost never considered in lean literature. This is because lean always begins with the Current State Map, carried out using VSM or other mapping techniques, and WLC is not included in the standard lean toolbox, that considers only Kanban and CONWIP as possible ways to streamline the manufacturing process. A first attempt for a more comprehensive analysis was formulated by Marangoni et al. (2013), who introduced a new mapping tool called Multiple-Value Stream Mapping (M-VSM). Unfortunately, at its present state, also M-VSM is of scarce interest for practitioners, as it is just a conceptual draft and is not sufficiently detailed for an industrial application.

The present paper starts from this point, with the objective to develop a new Mapping Tool for Make-To-Order job shops (MT-MTO or, from here on, 2MTO), that could facilitate the analysis and, later, the achievement of lean benefits in HVLV job-shops. Concerning the achievement of lean benefits, we anticipate that our focus will be on hybrid pull-oriented techniques, such as Workload Control (WLC), that are particularly suitable for MTO manufacturers (Bertolini et al., 2015; Stevenson et al., 2009). Our belief is that, although desirable, it is not always possible to move, directly, from a push to a pure-pull manufacturing environment, characterised by U-shaped cells and dedicated values streams. If flexibility is a key issue of competitiveness, a job-shop oriented layout, with Work-In-Process (WIP) accumulating between work centres, must be maintained. In these conditions the adoption of hybrid pull-oriented techniques for WIP control has to be considered as a better choice, since it can lead to WIP reduction and throughput time stabilization, without the need to overturn the original layout (Zammori, et al., 2016).

The remainder of the paper is organised as follows. After a brief analysis of the distinctive features of WLC, given in Section 2, the action research approach that led toward the definition of 2MTO is presented in Section 3. In the same section, we also introduce a set of fundamental questions, structured as a flowchart, for the analysis of the system and for the identification of the best way to achieve lean benefits. Section 3 is just an anticipation of Section 4, where each question will be unpacked and 2MTO will be explained in further details, referring to the industrial case where it was firstly originated and tested. Changes made to the manufacturing system and achieved lean benefits are detailed in Section 5. Lastly, we draw final comments and ideas for future researches in Section 6.

## 2 A brief introduction to Workload Control

Workload Control is a hybrid PPC system designed for MTO companies and, as noted by Stevenson et al. (2005), it is particularly suitable for HVLV job-shops, where it is fundamental to maintain a favourable balance between production flexibility and lead time’s variability. More precisely, the aim of WLC is to maintain WIP at a predefined level, to optimize the trade-off between high throughput rates and short and stable Lead Times (LT). To do so, WLC approaches the shop floor as a series of queues of jobs and it combines an order release mechanism with a pre-shop pool of orders that stabilises the performance of the manufacturing system, making it independent of possible variations in the stream of incoming orders (Bertrand and Van Ooijen, 2002). More specifically, the goal is to release jobs in the shop floor only if they do not exceed some pre-defined threshold limits known as “workload norms”. This keeps queues' length in front of each work centre as short as possible, without reducing throughput rates, so that WIP and LT can be stabilised and competitive prices and reliable due dates can be quoted (Stevenson et al. 2009).

What is important to stress is the fact that, despite a great deal of academic attention (Thürer et al., 2011), practitioners are not yet familiar with WLC (Soepenberg et al., 2012) and successful implementations are still rare, although increasing (Hendry et al., 2013; Silva et al., 2015). In this regard, according to Stevenson et al. (2010), a successful WLC implementation should go through three sequential phases:

1. Pre-implementation - A preliminary assessment is made to see if WLC is adequate for the manufacturing system under analysis;
2. Implementation - The operating parameters of WLC are set and fine-tuned;
3. Post-implementation - Obtained performances are periodically measured and used to dynamically readjust the operating parameters of WLC.

To the best of our knowledge, academicals have mainly focused on the last two points and, despite its practical relevance, the pre-implementation stage has been addressed only by a few works (Henrich et al., 2004; Silva et al., 2015). Accordingly, our aim is to define a new analysis and mapping tool for WLC implementation covering all the above-mentioned phases, focusing on the first one. Our hope is that the availability of a tool for the assessment of WLC could disseminate this technique and, eventually, increase the number of success stories of WLC.

## 3 2MTO: basics of the proposed framework

2MTO was developed as the result of a practical action research, part of a lean project carried on by an Italian manufactured with 25 employees and an average turnover of € 3,500,000 per year. The company can be classified as a Small-Medium Enterprise (SME). Due to secrecy reasons, the name of the SME must remain screened, and so it will be referred as I-SME. For the same reason, some data have been purposely modified, without altering the overall outcomes we have obtained.

### 3.1 Background of I-SME

The core business of I-SME is the production of high precision mechanical parts used in sport and racing cars (e.g. motor casings, shafts, etc.) and, in a smaller percentage, in luxury cars. In both cases, production starts on customers' orders and parts are manufactured to the customer's specifications. Thus, products' variability is very high and, to assure an adequate level of flexibility, production is organized as a job-shop, with machines grouped into three main departments:

1. Sand blasting - this department contains two sand blasting chambers ($BC_1$ and $BC_2$) used to clean and smooth the surfaces of casted or moulded mechanical parts;
2. Machining - this department is the core of the shop floor, where most of the production cycle takes place. Nine Work Centres (WCs) are installed herein:
    i. three turning machines: $WC_1$, $WC_2$ and $WC_3$;
    ii. two milling machines: $WC_4$ and $WC_5$;
    iii. one drilling machine: $WC_6$;
    iv. three grinding machines: $WC_7$, $WC_8$ and $WC_9$;
3. Quality control and packaging - this department consists in a quality control station (QC), where items are inspected and, if in compliance, packaged for shipping.

Also, to cope with variability, I-SME uses an Enterprise Resource Planning, equipped with a specific module for production management and control, which operates on shop floor data, collected in real time through a Manufacturing Executing Systems (MES). Nonetheless, production planning is perceived as one of the main problems and manufacturing performances are not satisfactory. In particular, LTs are long and variable and so, when contracting due dates with end customers, I-SME runs the risk of accepting orders that are unlikely to be delivered on time. The rate of orders that fulfil due dates is just above 70%, with serious economic consequences, both in terms of penalties and reduced margins.

### 3.2 Action research approach

The above-mentioned situation was particularly critical because, being unaware of the root causes of the problem, I-SME reacted to delays by pushing urgent jobs in production and prioritizing them by means of simple dispatching rules (such as the Earliest Due Date). However, this approach worsened the problem, as the result was a further increase of WIP levels and queues. These issues prompted I-SME, in 2014, to look for alternative solutions such as lean manufacturing; yet, the lack of standard approaches for lean in MTO HVLV job-shops appeared, immediately, as a relevant hindrance.

Thus, I-SME set up a convention with an Italian University for a research project (2014 – 2015) aiming to streamline the manufacturing process and, at the same time, to answer to the following research question*: "How is it possible to achieve long lasting lean benefits in a MTO-HVLV manufacturing system?"*

To unpack this question, it is necessary to:

- Understand the peculiarities of the system under analysis.
- Define a framework to identify the lean approaches more appropriate for the system.
- Follow the framework and improve the system.
- Assess if improvements in key performance indicators were achieved.

In our case, an action research approach was adequate, due to the need to involve practitioners of the company in the analysis and framework definition, to actively participate in the improvement process and assess its outcomes.

As noted by Hendry et al. (2013), to assure the success of an action research, two issues are essential: (i) Effective roles and relationships and (ii) Appropriate data collection methods.

Concerning the first point, there is the need to ensure good relationships and to avoid potential conflicts between research and business objectives (Baskerville and Wood-Harper 1996). This was eased in I-SME due to the pressing need of improving its performances. However, we decided to build a well-balanced inter-functional team, comprehending the logistics manager, the quality manager, the production manager and the heads of the sand-blasting and machining departments. Two academic experts, with a supervisory role, and a full-time PhD student were also engaged in the team.

The team set the following goals on key performance indicators: *(i)* to raise on-time deliveries above 90% and *(ii)* to reduce WIP by 50%. Also, due to the financial position of I-SME, an additional objective was that to develop and implement effective lean solutions, without the need of large investments, at least in the short-medium term.

Regarding the second key issue for ensuring high quality outcomes, the team decided to use quantitative data (as detailed in Section 4) collected, mainly, from the company's ERP. Some of the extracted data (around 10%) were verified through direct observations and missing data were collected, directly, on the shop floor. Also, we observe that, during a preliminary meeting, the team decided to:

- Map the 'As-Is' state, to identify the root causes of manufacturing inefficiencies;
- Analyse data and define an action plan for improvement;
- Change and/or optimize the current PPC system, to achieve the desired lean benefits.

### 3.3 Basics of the 2MTO

According to lean principles, machines' sharing should be avoided and a job-shop layout should be progressively converted into a multiple flow-shop with dedicated routes (Womack and Jones, 2003). However, most of the times, this vision is utopic and, even if specific routes could be assigned to the products with the highest demand rate, a job-shop configuration should be maintained to manufacture all the other low-volumes products. A more realistic goal is that to minimize routing's overlapping and machines' sharing, by considering actions such as layout modifications, machines duplication and replacement of monument-type equipment. Once these changes have been made, there is the need to select and dimension a suitable PPC system for WIP control and for a detailed production scheduling. It is thus paramount to be sure that the characteristics of the shop floor and that of the PPC system are compatible. Unfortunately, literature in the subject matter is rather scarce and there is often disagreement about which PPC system is more suitable in a specific condition (Germs and Riezebos, 2010).

Starting from these considerations, and well aware that a general rule cannot be formulated, the project team tried to define the road map (i.e., 2MTO) that should be followed, to address the above-mentioned issues. Specifically, as shown in the flowchart of Figure 1, a series of concatenated logical questions were articulated to take the right decisions, concerning how to:

- Map the 'As-Is' state of MTO job-shops;
- Define an action plan for future improvements;
- Select and dimension a proper PPC system, capable to generate lean benefits in the short-medium term and with little investments.

Please note that the flowchart of Figure 1 is the main outcome of the lean project carried on at I-SME. As known, action research is characterised by several cycles of intervention and reflection (Coughlan and Coghlan 2009), thus the questions and their logical connections were iteratively improved and re-defined, thanks to the experience gained during the project, as it will be detailed in the next Section.

However, for the sake of clarity, we want to conclude this section with a preliminary discussion concerning the rationale behind the questions and the way in which they were articulated.

Specifically, Question #1 evaluates if the system is suitable for a standard lean implementation. If so, standard mapping tool, such as VSM or Improved-VSM (IVSM) by (Braglia et al., 2006), and lean oriented PPC systems, such as Dual Kanban and CONWIP, are suggested (Bertolini and Romagnoli 2013).

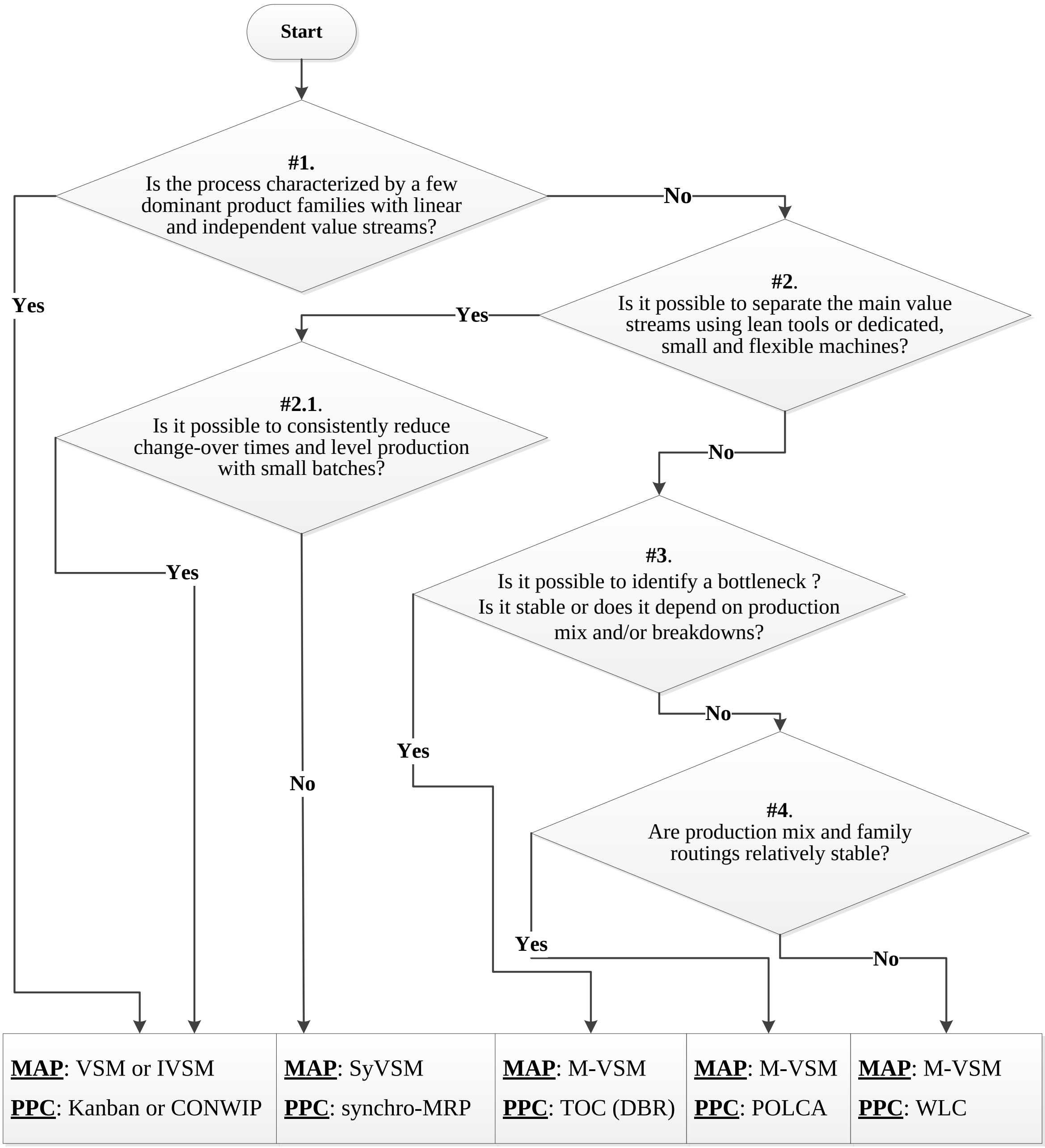


**Figure 1.** The 2MTO flowchart - how to select the best mapping tool and PPC system

If it is not so, Question #2 considers if the application of standard lean tools and, eventually, machines simplification and/or duplication, may be enough to limit interdependencies among value streams. Typical lean tools considered at this point are rapid changeover (SMED), cleaning and standardisation (5S), fool proof devices (Poka-Yoke), Continuous Improvement

(Kaizen), Total Productive Maintenance (TPM). If these actions are sufficient, and if changeover times are negligible or reducible (i.e., Question #2.1), the analysis proceeds as usual (Question #¦1). Conversely, if changeover times are significant, the analysis is diverted toward the implementation of Synchro-MRP following the advices of the Sy-VSM proposed by Bertolini et al. (2013).

If the answer to both questions #1 and #2 is “No”, a more comprehensive analysis is needed and so an improved version of the M-VSM approach - as detailed in Section 4 - is indicated as the best mapping tool. However, in this case, different PPCs may be used, according to the shop floor under analysis.

Questions #3 and #4 are used to shed light on this issue, and the presence of one or more shifting bottlenecks is used as the main discriminating criterion. Specifically, when a single bottleneck can be clearly identified, then Theory Of Constraints (TOC) - for example in the form of Drum Buffer Rope (DBR) - is, probably, the best approach, as it was specifically designed to handle such situations (Atwater and Chakravorty, 2002).

In case of shifting bottlenecks, a fact that may be due either to high variability of production mix or to high standard deviation of processing times, then the best possible alternative is to implement non-bottleneck based PPCs, such as Paired cell Overlapping Loops of Cards with Authorization (POLCA) or WLC (Lödding, Yu, and Wiendahl 2003).

The aim of Question #5 is exactly to discriminate between these two options. When production mix and family routings are relatively stable, POLCA is the preferable solution, whereas WLC is more suited when production mix and routings change frequently.

## 4 Application of 2MTO: the I-SME project

In this section, we will use the I-SME case to further explain the questions of the 2MTO framework, showing which techniques can be used to properly address each one of them.

## 4.1 Question #1: *«Is the manufacturing process characterised by a few dominant parts' families with linear and independent value streams?»*

The common thread among lean initiatives is the need to start from a deep understanding of the 'As-Is' state of the manufacturing process that must be improved. To this aim, well-known mapping tools such as VSM can be used (Gupta, 2005). So, the first question is: *«Which value stream(s) shall we map?»*

Answering is quite easy in a flow-shop, where the variety of manufactured parts is not too wide and a simple Pareto analysis (made in terms of parts and volumes) is enough to identify the target of the analysis. Conversely, in a MTO job-shop, focusing on few manufactured parts is inadequate to get a consistent picture of the whole production system. On the other one hand, mapping all value streams may be unfeasible, as the number of different parts can easily exceed the hundreds and, above all, because the system frequently processes new customised parts, which were never made before.

Thus, the only solution is to analyse the system in average terms, by aggregating parts with similar routings into families. As a general advice, part's family formation should be made following a two steps procedure: *(i)* a first aggregation should be obtained by considering the sequence with which departments are visited and, next *(ii)* the analysis should be refined splitting coarse groups into detailed families, depending on the exact sequence with which work-centres are visited. Anyhow, if the identified families can be considered independent, then the job shop can be converted in a generalized flow shop and standard lean tools can be applied, so as to deploy a pull oriented and levelled manufacturing process. These considerations are summarized by Question #1.

### *4.2.1 Data gathering and formation of parts' families at an aggregated level*

Part families' formation started with the retrieval of data concerning past production orders, in terms of *(i)* routings and *(ii)* production volumes. Unfortunately, using I-SME data, we were not able to pre-cluster parts using their routings at the departments' level, as the majority of them passed through all three departments. However, the analysis brought to light that most of the parts were dimensional variants of fourteen basic product configurations or jobs ($J_1$ to $J_{14}$), whose detailed routings and production volumes (expressed as percentage values) are shown in Table 1. These basic jobs were used to create a first aggregation of parts into families.

**Table 1.** Jobs' Routings

| | **Visited Departments and Work-Centres** | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | **Jobs** | **$Q_{\%}$** | **Sand Blasting** | **Machining** | | | | | | **Quality Control** |
| **Basic configurations (i.e., jobs)** | **$J_1$** | 4.4% | $BC_1$ | $WC_2$ | $WC_4$ | $WC_6$ | $WC_2$ | $WC_4$ | $WC_8$ | QC |
| | **$J_2$** | 11.6% | $BC_2$ | $WC_2$ | $WC_4$ | $WC_6$ | $WC_4$ | $WC_8$ | - | QC |
| | **$J_3$** | 18.3% | $BC_1$ | $WC_1$ | $WC_4$ | $WC_6$ | $WC_7$ | - | - | QC |
| | **$J_4$** | 7.7% | $BC_1$ | $WC_1$ | $WC_4$ | $WC_1$ | $WC_6$ | $WC_7$ | - | QC |
| | **$J_5$** | 4.5% | $BC_2$ | $WC_3$ | $WC_5$ | $WC_6$ | $WC_5$ | $WC_9$ | - | QC |
| | **$J_6$** | 3.7% | $BC_1$ | $WC_2$ | $WC_5$ | $WC_6$ | $WC_3$ | $WC_6$ | $WC_8$ | QC |
| | **$J_7$** | 8.5% | $BC_1$ | $WC_2$ | $WC_4$ | $WC_6$ | - | - | - | QC |
| | **$J_8$** | 7.2% | $BC_2$ | $WC_3$ | $WC_5$ | $WC_6$ | - | - | - | QC |
| | **$J_9$** | 9.6% | $BC_1$ | $WC_2$ | $WC_5$ | $WC_6$ | $WC_8$ | - | - | QC |
| | **$J_{10}$** | 10.6% | $BC_2$ | $WC_3$ | $WC_5$ | $WC_1$ | - | - | - | QC |
| | **$J_{11}$** | 2.3% | $BC_2$ | $WC_2$ | $WC_5$ | $WC_6$ | $WC_9$ | - | - | QC |
| | **$J_{12}$** | 3.8% | $BC_1$ | $WC_1$ | $WC_4$ | $WC_2$ | $WC_4$ | $WC_6$ | $WC_7$ | QC |
| | **$J_{13}$** | 4.9% | $BC_2$ | $WC_3$ | $WC_5$ | $WC_6$ | $WC_9$ | - | - | QC |
| | **$J_{14}$** | 2.9% | $BC_2$ | $WC_2$ | $WC_5$ | $WC_6$ | $WC_3$ | $WC_5$ | $WC_8$ | QC |

Table 1 clearly shows: the absence of a dominant configuration, the presence of machines commonalities and the existence of non-linear routings. Consequently, it is reasonable to expect a negative answer to Question #1; this will be confirmed in the next Sub-Section.

### *4.2.2 Parts families formation at a detailed level*

To ascertain this situation, we refined the grouping using the framework for *"machine-part cell formation"* suggested by Braglia et al. (2006):

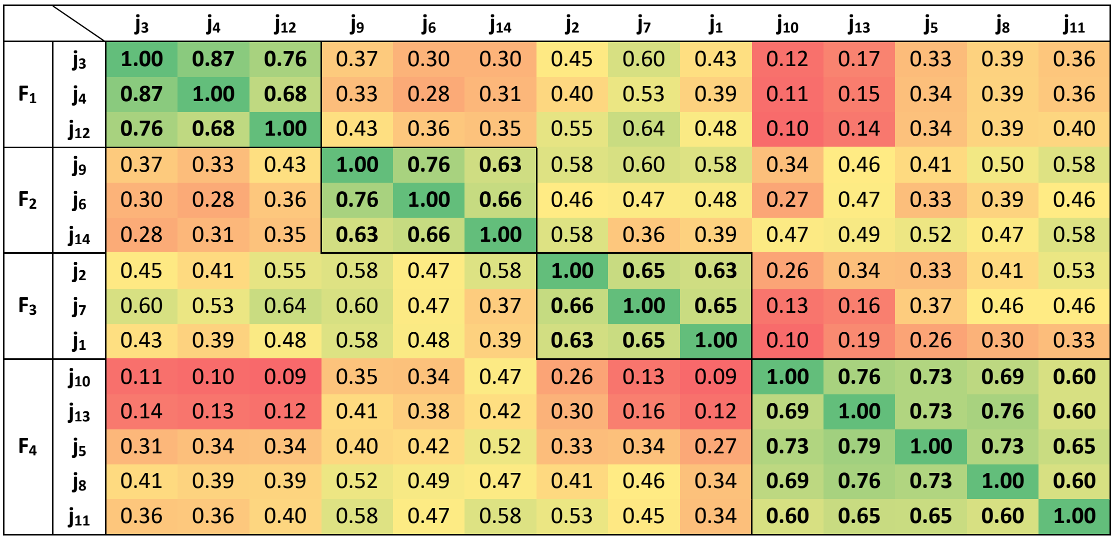
- Routings of the 14 jobs were used to build the squared and symmetric Similarity Matrix **S**[$\boldsymbol{s_{ij}}$], containing the Pair Wise Similarity Coefficients $s_{ij}$ between job $i$ and job $j$;
- **S**[$\boldsymbol{s_{ij}}$] was used as the input of an aggregative hierarchical clustering procedure;
- As a result, we obtained the clusters maximizing the similarity among jobs.

In the original framework, clusters are based on the well-known Jaccard's similarity index. However, we believe that this is not the best option for a job-shop, as the Jaccard's similarity index considers neither the sequence nor the frequency (i.e., number of visits per routing) with which machines are visited. To get a more robust solution, we suggest using the Bypassing Moves and Idle Machines (BMIM) similarity coefficient proposed by Goyal et al. (2012), which expressly considers all the above mentioned issues. By doing so we obtained the similarity matrix of Table 2, which indicates that jobs can be conveniently clustered into the following four families:

- $F_1 \{J_3, J_4, J_{12}\}$ - Similarity = 0.68, Manufactured quantity $Q_{\%,1}$ = 29.8%
- $F_2 \{J_9, J_6, J_{14}\}$ - Similarity = 0.63, Manufactured quantity $Q_{\%,2}$ = 16.2%
- $F_3 \{J_2, J_7, J_1\}$ - Similarity = 0.63, Manufactured quantity $Q_{\%,3}$ = 24.5%
- $F_4 \{J_{10}, J_{13}, J_5, J_8, J_{11}\}$ - Similarity = 0.60, Manufactured quantity $Q_{\%,4}$ = 29.5%

As it can be seen, clusters are homogeneous and well defined and the robustness of this partitioning is testified by a very low number of similarity values greater than 0.60 among the jobs of different clusters.

**Table 2.** BMIM Similarity matrix at I-SME



| | | $j_3$ | $j_4$ | $j_{12}$ | $j_9$ | $j_6$ | $j_{14}$ | $j_2$ | $j_7$ | $j_1$ | $j_{10}$ | $j_{13}$ | $j_5$ | $j_8$ | $j_{11}$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $F_1$ | $j_3$ | **1.00** | **0.87** | **0.76** | 0.37 | 0.30 | 0.30 | 0.45 | 0.60 | 0.43 | 0.12 | 0.17 | 0.33 | 0.39 | 0.36 |
| | $j_4$ | **0.87** | **1.00** | **0.68** | 0.33 | 0.28 | 0.31 | 0.40 | 0.53 | 0.39 | 0.11 | 0.15 | 0.34 | 0.39 | 0.36 |
| | $j_{12}$ | **0.76** | **0.68** | **1.00** | 0.43 | 0.36 | 0.35 | 0.55 | 0.64 | 0.48 | 0.10 | 0.14 | 0.34 | 0.39 | 0.40 |
| $F_2$ | $j_9$ | 0.37 | 0.33 | 0.43 | **1.00** | **0.76** | **0.63** | 0.58 | 0.60 | 0.58 | 0.34 | 0.46 | 0.41 | 0.50 | 0.58 |
| | $j_6$ | 0.30 | 0.28 | 0.36 | **0.76** | **1.00** | **0.66** | 0.46 | 0.47 | 0.48 | 0.27 | 0.47 | 0.33 | 0.39 | 0.46 |
| | $j_{14}$ | 0.28 | 0.31 | 0.35 | **0.63** | **0.66** | **1.00** | 0.58 | 0.36 | 0.39 | 0.47 | 0.49 | 0.52 | 0.47 | 0.58 |
| $F_3$ | $j_2$ | 0.45 | 0.41 | 0.55 | 0.58 | 0.47 | 0.58 | **1.00** | **0.65** | **0.63** | 0.26 | 0.34 | 0.33 | 0.41 | 0.53 |
| | $j_7$ | 0.60 | 0.53 | 0.64 | 0.60 | 0.47 | 0.37 | **0.66** | **1.00** | **0.65** | 0.13 | 0.16 | 0.37 | 0.46 | 0.46 |
| | $j_1$ | 0.43 | 0.39 | 0.48 | 0.58 | 0.48 | 0.39 | **0.63** | **0.65** | **1.00** | 0.10 | 0.19 | 0.26 | 0.30 | 0.33 |
| $F_4$ | $j_{10}$ | 0.11 | 0.10 | 0.09 | 0.35 | 0.34 | 0.47 | 0.26 | 0.13 | 0.09 | **1.00** | **0.76** | **0.73** | **0.69** | **0.60** |
| | $j_{13}$ | 0.14 | 0.13 | 0.12 | 0.41 | 0.38 | 0.42 | 0.30 | 0.16 | 0.12 | **0.69** | **1.00** | **0.73** | **0.76** | **0.60** |
| | $j_5$ | 0.31 | 0.34 | 0.34 | 0.40 | 0.42 | 0.52 | 0.33 | 0.34 | 0.27 | **0.73** | **0.79** | **1.00** | **0.73** | **0.65** |
| | $j_8$ | 0.41 | 0.39 | 0.39 | 0.52 | 0.49 | 0.47 | 0.41 | 0.46 | 0.34 | **0.69** | **0.76** | **0.73** | **1.00** | **0.60** |
| | $j_{11}$ | 0.36 | 0.36 | 0.40 | 0.58 | 0.47 | 0.58 | 0.53 | 0.45 | 0.34 | **0.60** | **0.65** | **0.65** | **0.60** | **1.00** |

### *4.2.3 Graphical representation of families' routings*

We also mapped the value stream of each family using an enriched spaghetti diagram, as shown by Figure 2. At first, we reproduced the block layout of the shop floor, indicating each department and the number of work centres installed in each one of them. Next, to visualize material flows, we used oriented arrows to sketch the main routing of each part family. Note that, to increase the information content of the diagram, we drew arrows with different colours and with a size proportional to the volume of the corresponding material flow. Also, anytime an arrow passes through a department, a number is used to indicate how many work centres (of that department) are visited by a specific family.

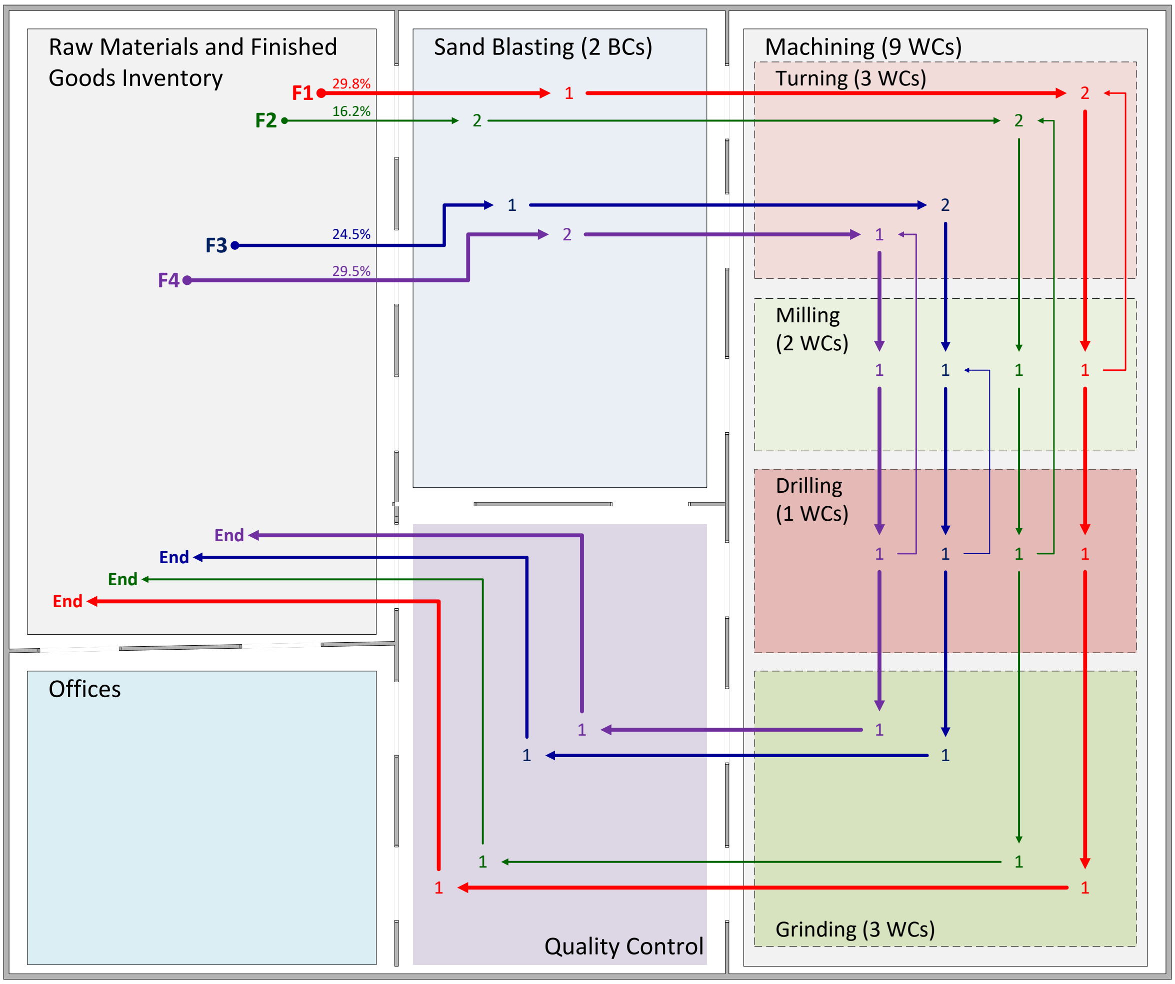


**Figure 2.** I-SME enriched spaghetti diagram

We enriched the diagram even further, by drawing the sub-areas of the machining department where similar work centres are located (i.e., turning, milling, drilling and grinding). In this way, it becomes clear that, although a dominant U-shaped material flow exists, a relevant quota of the jobs has a multi-directional routing with recirculation i.e., some of the work centres are visited more than once. Although these flows are not relevant in terms of volume, they should not be overlooked, as they could complicate material handling and internal logistics, in a pull-oriented configuration.

To conclude, as Tables 1 and Figure 2 clearly show, I-SME:

- Is characterised by four parts families, that are all important in terms of turnover;
- Routings are not independent and there are many work centres shared by all families.

Consequently, the answer to Question #1 is “No”.

### *4.2* Question #2: *«Is it possible to separate value streams using lean tools or dedicated, small and flexible machines?»*

Using the words by Womack and Jones (2003), in order to level production on the Takt Time and to balance machines’ cycle times, lean manufacturing requires that *“each machine can be converted almost instantly from one product specification to the next one”* and that *“many traditional massive machines [...] should be right-sized to fit directly in the production process.”* These conditions are hardly achievable in case of machines that are shared by imbalanced value streams; in such cases, flow is frequently interrupted, as parts, coming from different areas, converge on the shared machines. A straightforward solution is that to separate flows, by purchasing smaller and more flexible equipment, or more “flow-friendly” technologies dedicated to each value stream. Unfortunately, this option is not always possible, or it may be cost prohibitive, especially in case of *monument-type* shared machine i.e., massive, batch-oriented, equipment, that are costly or disruptive to move and that are very difficult to be resold. In such cases, monuments should be detached from the main value stream, managed using a batch production approach and, not to disrupt flow and synchronization, specific pull systems - such as Signal Kanban (Braglia et al. 2006; Nash and Poling 2008) - should be properly implemented. These concepts are synthetized by Question #2.

### 4.2.1 *The machines' sharing table*

Owing to the above mentioned issued it is crucial to:

- Identify shared machines;
- Compute their average workload;
- Determine if they can be classified as monument-type machines.

To get this fundamental information, there is the need to collect additional data on batch dimensions, processing and changeover times; also, these data should be organized as in Table 3. The first six columns report basic information concerning parts' families, in terms of total processed volumes (i.e., average arrival rate and batch size) and of their routing at the department level. The other columns refer to the work-centres and show the Machining Time ($\mathrm{MT}_{\mathrm{F_i,k}}$), expressed as hours per day, that each work-centre *k* is expected to dedicate to the jobs belonging to family $\mathrm{F_i}$. Table 3 also contains some qualitative information, as it clearly shows: *(i)* how many families are processed by each work centre, *(ii)* which are the monument-type machines and *(iii)* which are the batch-processing machines. Concerning the expected machining times, these values were estimated as in Eq. (1), starting from the data collected from the ERP:

$$MT_{F_i,k} = \sum_{j\in F_i} (\lambda_j \cdot n_{j,k} \cdot b_j) \cdot t_{j,k} = \sum_{j\in F_i} (v_{j,k} \cdot b_j) \cdot t_{j,k} = \sum_{j\in F_i} q_{j,k} \cdot t_{j,k} = \\ = \sum_{j\in F_i} MT_{j,k} \tag{1}$$

Where:

- $\lambda_j$ is the average arrival rate of job *j*;
- $n_{j,k}$ is the number of times that machine *k* recurs in the routing of job *j*;
- $b_j$ is the average batch size of job *j*;
- $t_{j,k}$ is the average processing time of job *j* on machine *k*;
- $v_{j,k} = (\lambda_j \cdot n_{j,k})$ is the average number of jobs *j*, per time unit, processed by machine *k*;

- $q_{j,k} = (v_j \cdot b_j)$ is the average number of jobs $j$ (per unit of time) processed by machine $k$;
- $MT_{j,k}$ is the machining time per unit of time of job $j$ on machine $k$.

**Table 3.** Machines' Sharing

| Average features of parts' families | | | | | | Dep. #1 Sand Blas. | | Dep. #2 Machining | | | | | | | | | Dep. #3 Quality |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Family** | **# Jobs** | **Variants** | **Arrival Rate** | **Job Order Batch Size** | **Dept. Routing** | **BC1** | **BC2** | **WC1** | **WC2** | **WC3** | **WC4** | **WC5** | **WC6** | **WC7** | **WC8** | **WC9** | **QC** |
| $F_1$ | 3 | 75 | 1.6 [jobs/day] | 15 | 1-2-3 | 2.2 [h/d] | - | 5.7 [h/d] | 0.2 [h/d] | - | 3.7 [h/d] | - | 2.5 [h/d] | 5.4 [h/d] | - | - | 1.7 [h/d] |
| $F_2$ | 3 | 63 | 0.9 [jobs/day] | 25 | 1-2-3 | 0.9 [h/d] | 0.4 [h/d] | - | 1.6 [h/d] | 0.8 [h/d] | - | 2.2 [h/d] | 1.4 [h/d] | - | 2.5 [h/d] | - | 1.1 [h/d] |
| $F_3$ | 3 | 50 | 1.3 [jobs/day] | 10 | 1-2-3 | 0.8 [h/d] | 1.2 [h/d] | - | 2.8 [h/d] | - | 3.0 [h/d] | - | 1.3 [h/d] | - | 2.6 [h/d] | - | 1.6 [h/d] |
| $F_4$ | 5 | 162 | 1.6 [jobs/day] | 20 | 1-2-3 | - | 3.3 [h/d] | - | 0.3 [h/d] | 3.6 [h/d] | - | 4.0 [h/d] | 1.6 [h/d] | - | - | 5.3 [h/d] | 1.5 [h/d] |
| **Total number or processed families** | | | | | | **3** | **3** | **1** | **4** | **2** | **2** | **2** | **4** | **1** | **2** | **1** | **4** |
| **Batch Processing Machine** | | | | | | ✓ | ✓ | | | | | | | | | | |
| **Monument-Type** | | | | | | ✓ | ✓ | | ✓ | | ✓ | ✓ | | | | | |

For instance, if we consider $WC_4$, a monument-type milling machine that processes both families $F_1 \equiv \{J_3, J_4, J_{12}\}$ and $F_3 \equiv \{J_2, J_7, J_1\}$, using data of Table 4 we have that:

$$MT_{F_1,WC_4} = \sum\nolimits_{j\in F_1} \left(v_{j,WC_4} b_j\right) t_{j,WC_4} = (0.12\cdot 1\cdot 13)\cdot 7.5 + (0.05\cdot 1\cdot 17)\cdot 6.6$$

$$+ (0.03\cdot 2\cdot 20)\cdot 8.5 \cong 27.4\left[\frac{min}{hour}\right]$$

$$MT_{F_3,WC_4} = \sum\nolimits_{j\in F_3} \left(v_{j,WC_4} b_j\right) t_{j,WC_4} = (0.08\cdot 1\cdot 22)\cdot 3.6 + (0.08\cdot 1\cdot 18)\cdot 4$$

$$+ (0.06\cdot 2\cdot 20)\cdot 4.2 \cong 22.2\left[\frac{min}{hour}\right]$$

**Table 4.** Input data of family $F_1$ and $F_3$ at work-centre $WC_4$

| **Job** | $\boldsymbol{\lambda_j}$ | $\boldsymbol{n_{j,WC_4}}$ | $\boldsymbol{b_j}$ | $\boldsymbol{t_{j,WC_4}}$ |
|---|---|---|---|---|
| $J_3$ | 0.12 [jobs/hour] | 1 | 13 | 7.5 [min] |
| $J_4$ | 0.05 [jobs/hour] | 1 | 17 | 6.6 [min] |
| $J_{12}$ | 0.03 [jobs/hour] | 2 | 20 | 8.5 [min] |
| $J_2$ | 0.08 [jobs/hour] | 1 | 23 | 5.6 [min] |
| $J_7$ | 0.06 [jobs/hour] | 1 | 18 | 6.0 [min] |
| $J_1$ | 0.03 [jobs/hour] | 2 | 16 | 5.7 [min] |

Similarly, arrival rates and batch sizes (of Table 3) were computed as follows:

Arrival rate $\Lambda_{F_1} = \sum_{J\in F_1} \lambda_J = \lambda_{J_3} + \lambda_{J_4} + \lambda_{J_{12}} = 0.2\left[\frac{jobs}{hour}\right] \equiv 1.6\left[\frac{jobs}{day}\right]$;

Batch Size $B_{F_1} = \sum_{J\in F_1}\left(\frac{\lambda_J}{\Lambda_{F_1}}\cdot b_J\right) = (0.61\cdot 13 + 0.26\cdot 17 + 0.13\cdot 20) = 15.$

In our case, all required data were easily and rapidly collected from the company's ERP and MES. This was a clear advantage. However, especially in SMEs, historical data are not always available. Nonetheless this should not be considered as a deterrent to the implementation of 2MTO, as data could be collected directly on the shop floor, using an approximated analysis. It is sufficient to neglect changeover times and measure processing times directly on the field, as in standard VSM. To this aim, anytime a production order is processed, it should be classified as belonging to a specific Family, according to its routing and, next, its processing time at each machine can be registered.

Returning to the I-SME case, it emerged a high degree of machines' sharing and the practical impossibility to separate all value streams. Indeed, only three work centres are dedicated to a single family, whereas all the other ones, including five monuments, are shared.

More specifically, due to technological constraints, the sand blasting machines cannot be substituted, but this problem could be bypassed using Signal Kanban to decouple the sand-blasting and the machining departments. The real problem is due to machines' sharing at the machining department and to the presence of two monuments in the same department. Here, the only possibility could be that to purchase smaller and more flexible machines, but unfortunately, monuments are not yet amortized and they do not have much market: writing them off would generate a capital loss that is unbearable for a small company such as I-SME.

For the above-mentioned reasons, also the answer to question #2 is "No" and so, to achieve lean benefit, I-SME decided to choose a proper hybrid PPC technique (to synchronize flows and to stabilize WIP), well aware that the long-term goal is to get rid-off all monuments and to redefine the internal layout of the machining department.

### 4.3 Question #3: *«Is it possible to identify a single bottleneck that does not vary due to production mix, processing times and/or to breakdowns? »*

Another crucial issue concerns the identification of potential bottlenecks i.e., those work centres that, depending on the production mix, processing times and/or to frequent breakdowns, may have a very high utilisation rate.

The utilisation $U_k$ of machine *k* can be obtained as the ratio of the active and of the available time, as clearly shown by Eq. (2):

$$U_k = \frac{1}{(H \cdot UT_k)} \sum\nolimits_{F_i} (TT_{F_i,k}) \tag{2}$$

Where:

- $H$ is the total number of working hours available per day;
- $UT_k \leq 1$ is the Up Time of work-centre $k$;
- $TT_{F_i,k}$ is the Total active Time that work-centre $k$ is expected to dedicate, per unit of time, to the jobs of family $F_i$.

Also, since the active time $TT_{F_i,k}$ includes both machining and changeover, the utilization can be computed as in Eq. (3).

$$U_k = \sum\nolimits_{F_i} \frac{\left(MT_{F_i,k} + \sum_{j \in F_i}(COT_{j,k})\right)}{(H \cdot UT_k)} \tag{3}$$

Where $COT_{j,k}$ is the changeover time that machine $k$ is expected to dedicate to job $j$ per unit of time.

Please note that, whereas $MT_{F_i,k}$ is evaluated at the family level, $COT_{j,k}$ is evaluated at the job level. This is because, in general, changeover may be sequence dependent and it may also be needed for jobs belonging to the same family, as detailed explained in the following Sub-section.

### *4.3.1 The potential bottlenecks table*

Generally speaking, if changeovers are sequence dependent, then $COT_{j,k}$ can be expressed as in Eq. (4).

$$COT_{j,k} = v_{j,k} \cdot \sum\nolimits_{j^* \neq j} c_{(j,j^*,k)} \cdot P(j^* \; on \; k) \coloneq v_{j,k} \cdot \sum\nolimits_{j^* \neq j} \left( c_{(j,j^*,k)} \cdot \frac{v_{j^*,k}}{V_k} \right) \tag{4}$$

Where the sum is made an all jobs $j^*$ other than $j$ and:

- $c_{j,j^*,k}$ is the average changeover time when job *j* is processed on work centre *k* after job $j^* \neq j$;
- $P(j^*\ on\ k)$ is the probability to find job $j^*$ on work centre *k*;
- $V_k = \sum_j v_{j,k}$ is the total number of jobs (per unit of time) processed by *k*.

To apply Eq. (5), we further elaborated the historical data of the ERP to understand if, for some work centres, $c_{(j,j^*,k)}$ could be considered as constant (i.e., it does not depend on the job) or, at least, sequence independent.

The analysis showed that, at some work centres changeover is constant, it is sequence independent and it is always performed, unless two identical jobs are processed one after the other. In this case $c_{(j,j^*,k)} = c_k$ if $j^* \neq j$ and it is zero otherwise; so, Eq. (4) simplifies as in (5).

$$COT_{j,k} = v_{j,k} \cdot c_k \cdot \left(1 - P(j\ on\ k)\right) = v_{j,k} \cdot c_k \left(1 - \frac{v_{j,k}}{V_k}\right) \cong \left(v_{j,k} \cdot c_k\right) \tag{5}$$

Where and $c_k$ can be simply evaluated as in Eq. (6).

$$c_k = \frac{Total\ Time\ For\ Changeover}{Number\ of\ Changeover\ Activities} \tag{6}$$

However, we also found some work centres where changeover is constant and where it is performed only if *j* and $j^*$ belongs to different families. That is: $c_{(j,j^*,k)} = 0$ if $j, j^* \in F_i$ and $c_{(j,j^*,k)} \equiv c_k$ otherwise; so, Eq. (4) modifies as in Eq. (7).

$$COT_{j,k} = v_{j,k} \cdot c_k \cdot \left(\frac{\sum_{j^* \notin F_i} v_{j^*,k}}{V_k}\right) = v_{j,k} \cdot c_k \cdot \left(1 - \frac{V_{i,k}}{V_k}\right) \tag{7}$$

Where $V_{i,k} = \sum_{j \in F_i} v_{j,k}$ is the total number of jobs belonging to family $F_i$ processed by *k*, per unit of time.

To clarify these concepts, let us consider, again, the monument type milling machine $WC_4$. Uptime is equal to 95%, changeover is executed only when production passes from family $F_1$

to F3 and, on average, it lasts 20 minutes. Since $v_{J_{12},WC_4} = 0.06 \left[\frac{jobs}{hours}\right]$, $V_{F_1,WC_4} = 0.23$ and $V_{F_3,WC_4} = 0.2$ (see Table 4) we finally have that:

$$COT_{J_{12},WC_4} = v_{J_{12},WC_4} \cdot c_k \cdot \left(1 - \frac{V_{F_1,WC_4}}{V_{F_1,WC_4} + V_{F_3,WC_4}}\right) = 0.48 \left[\frac{min}{hour}\right]$$

By repeating the same computation for all the jobs belonging to F1 and F3, we obtained $\sum_{j \in (F_1 \cup F_2)} \left(COT_{j,WC_4}\right) = 4.2 \left[\frac{min}{hour}\right]$

So, using the machining times $MT_{F_1,WC_4} = 27.4 \left[\frac{min}{hour}\right]$ and $MT_{F_3,WC_4} = 22.2 \left[\frac{min}{hour}\right]$ (see Table3) we obtained a utilisation level equal to:

$$U_{WC_4} = \frac{27.4 + 22.2 + 4.2}{0.95 \cdot 60} \cong 95\%$$

Obtained results are summarized in Table 5 that shows, for each work centre: *(i)* the average changeover time *c*, *(ii)* the changeover probability, *(iii)* the total working time TT, *(iv)* the share of TT that is due, respectively, to machining and to change over time, *(v)* the up-time UT and *(vi)* the utilisation level U.

**Table 5.** Potential Bottlenecks

| | **c** | **CO Prob.** | **TT** | **%MT** | **%COT** | **UT** | **U** |
|---|---|---|---|---|---|---|---|
| BC1 | 50 [min] | 61% | 5.4 [h/d] | 71% | 29% | 95% | **71%** |
| BC2 | 45 [min] | 48% | 5.7 [h/d] | 85% | 15% | 94% | **76%** |
| WC1 | 10 [min] | 15% | 5.8 [h/d] | 99% | 1% | 92% | **79%** |
| WC2 | 30 [min] | 84% | 61 [h/d] | 81% | 19% | 96% | **80%** |
| WC3 | 15 [min] | 80% | 4.8 [h/d] | 92% | 8% | 88% | **68%** |
| **WC4** | 20 [min] | 50% | 7.2 [h/d] | 92% | 8% | 95% | **95%** |
| WC5 | 10 [min] | 46% | 6.4 [h/d] | 97% | 3% | 95% | **85%** |
| **WC6** | 5 [min] | 90% | 7.2 [h/d] | 95% | 5% | 93% | **97%** |
| WC7 | 15 [min] | 20% | 5.4 [h/d] | 99% | 1% | 95% | **72%** |
| WC8 | 10 [min] | 50% | 5.2 [h/d] | 97% | 3% | 90% | **73%** |
| WC9 | 10 [min] | 20% | 5.3 [h/d] | 99% | 1% | 87% | **77%** |
| QC | 5 [min] | 90% | 6.2 [h/d] | 93% | 7% | 98% | **80%** |

Please note that the probability to perform a changeover can be obtained using the total probability formula, as shown in Eq. (8):

$$P(Changeover\ on\ k) = \sum_j P(j\ on\ k) \cdot P(changeover\ on\ k\ |j) \cdot$$

$$= \sum_j \left(\frac{v_{j,k}}{V_k}\right) \cdot \left(\sum_{j^* \in J_{j,k}} \frac{v_{j^*,k}}{V_k}\right) = \frac{1}{(V_k)^2} \cdot \sum_j \left(v_{j,k} \cdot \sum_{j^* \in J_{j,k}} v_{j^*,k}\right) \cdot \tag{8}$$

Where $J_{j,k}$ is the set of jobs for which job *j* requires changeover on work centre *k*.

Obviously, if changeover is always performed, then $J_{j,k}$ coincides with all the jobs except *j*; if changeover is executed only when a family changes, then $J_{j,k}$ coincides with all the jobs except those ones belonging to the family to which *j* belongs to.

For instance, in case of $WC_4$, from data of Table IV we have:

$$P(Changeover\ on\ WC_4) = \frac{\sum_{j \in F_1}\left(v_{j,k} \cdot \sum_{j^* \in F_4} v_{j^*,k}\right)}{\left(V_{WC_4}\right)^2} + \frac{\sum_{j \in F_3}\left(v_{j,k} \cdot \sum_{j^* \in F_1} v_{j^*,k}\right)}{\left(V_{WC_4}\right)^2}$$

$$= \frac{2 \cdot V_{F_1,WC_4} \cdot V_{F_3,WC_4}}{\left(V_{WC_4}\right)^2} = \frac{2 \cdot 0.23 \cdot 0.2}{0.43^2} = 0.497$$

Also, note that, at work centres $WC_1$, $WC_7$ and $WC_9$ the changeover probability is very low. This is because these work centres are dedicated to a single family and changeovers are rare.

From Table 5 it is easy to see that the production capacity of the manufacturing system is almost saturated. Indeed, although the average system's load is around 80%, a situation that can be generally considered as acceptable, there are two shifting bottlenecks (i.e., $WC_4$ and $WC_6$) with a very high average load of 95% and 97%, respectively. We must also consider that these values represent "net average loads", as they account neither for inbound logistics problems nor for machines' defects rates and/or other micro stoppages. Thus, at I-SME, it is very likely to observe periods of oversaturation, with WIP accumulating in queues and long waiting times. Consequently, also the answer to Question #3 is "No" and so a PPC system based on Theory Of Constraints must be discarded, because a single and stable bottleneck machine cannot be identified.

### 4.3.2 Additional lean oriented performance indicators

Before proceeding to step four, we completed the analysis of the 'As-Is' state by computing five Key Performance Indicator (KPIs), which will be used as benchmark for future improvements. In detail, these KPIs indicate different types of times that, on average, a job spends along its value stream:

- Value Added Time ($\mathrm{VAT}_{\mathrm{F_i}}$) - Total transformation time;
- Changeover Time ($\mathrm{CO}_{\mathrm{F_i}}$) - Total changeover time;
- Handling Time ($\mathrm{HT}_{\mathrm{F_i}}$) - Overall time spent for internal logistics;
- Waiting Time ($\mathrm{WT}_{\mathrm{F_i}}$) - Overall time spent in queue;
- Lead Time ($\mathrm{LTF_i}$) - Total time spent by a job along its value stream.

The first two indicators are calculated by aggregating the data of Sections 4.3 and 4.4, as in Eq. 9 and 10.

$$VAT_{F_i} = \sum\nolimits_{j\in F_i}\left(\frac{\lambda_i}{\Lambda_{F_i}}\cdot\sum\nolimits_k\left(b_j\cdot n_{j,k}\cdot t_{j,k}\right)\right) = \frac{\sum_k MT_{F_i,k}}{\Lambda_{F_i}} \tag{9}$$

$$CO_{F_i} = \frac{\sum_k \sum_{j\in F_i} COT_{j,k}}{\Lambda_{F_i}} \tag{10}$$

A few more words are needed to explain $\mathrm{HT}_{\mathrm{F_i}}$ and $\mathrm{WT}_{\mathrm{F_i}}$. If L is the set of all locations (both inventories and departments) in which the manufacturing plant can be ideally subdivided and $d_{j,(l\rightarrow m)}$ is the travelling time needed by job *j* to cover the distance between locations *l* and *m*, then the $\mathrm{HT}_{\mathrm{F_i}}$ can be calculated as in Eq. (11).

$$HT_{F_i} = \sum\nolimits_{j\in F_i}\left(\frac{\lambda_i}{\Lambda_{F_i}}\cdot\sum\nolimits_{l\in L} d_{j,(l\rightarrow m)}\right) \tag{11}$$

For instance, at I-SME we considered six different locations: (0) Raw Materials and Finished Good Inventory, (1) Sand Blasting, (2) Turning area, (3) Milling area, (4) Drilling area, (5) Grinding area and (6) Quality Control.

To compute $\mathrm{WT}_{\mathrm{F_i}}$, there is the need to estimate the average $WIP_{F_i,k}$ level of  for each part family $\mathrm{F_i}$ in each buffer $k$. It is important to note that the only way to estimate $WIP_{F_i,k}$ is to go, directly, on the shop floor and count the number of jobs accumulating in each buffer. Once these data have been collected, the expected waiting time $w_k$ at $k$ can be evaluated taking the product of $WIP_{F_i,k}$ and of the expected machining and changeover time, as shown in Eq. (12):

$$w_k = \sum\nolimits_{i\in F_i} \left( WIP_{F_i,k} \cdot \left( VAT_{F_{i,k}} + CO_{F_{i,k}} \right) \right) \tag{12}$$

Finally, the overall waiting time $\mathrm{WT}_{\mathrm{F_i}}$ can be computed as in Eq. (13).

$$\mathrm{WT}_{\mathrm{F_i}} = \sum\nolimits_{j\in F_i} \left( \frac{\lambda_i}{\Lambda_{F_i}} \cdot \sum\nolimits_{k} \left( n_{j,k} \cdot w_k \right) \right) \tag{13}$$

Concerning I-SME, values of these KPIs are summarised in Table 7.

**Table 7.** Lean KPI of the actual state

| | VAT | CO | HT | WT | LT |
|---|---|---|---|---|---|
| **Family F₁** | 13 [h] | 0.85 [h] | 0.6 [h] | 80.5 [h] | 95 [h] |
| **Family F₂** | 12.6 [h] | 1.7 [h] | 0.6 [h] | 100 [h] | 115 [h] |
| **Family F₃** | 10 [h] | 1.5 [h] | 0.58 [h] | 55 [h] | 67 [h] |
| **Family F₄** | 12 [h] | 0.7 [h] | 0.54 [h] | 41 [h] | 54 [h] |

As it often occurs, $\mathrm{VAT}_{\mathrm{F_i}}$ only accounts for a small percentage of $\mathrm{LT}_{\mathrm{F_i}}$ (11% ÷ 22%); conversely, $\mathrm{WT}_{\mathrm{F_i}}$ accounts for a big percentage of $\mathrm{LT}_{\mathrm{F_i}}$ (76% ÷ 87%). So, there is much room for future improvements and the introduction of pull-oriented PPC techniques may lead to a rapid achievement of significant benefits.

As above mentioned, I-SME had to maintain a job shop configuration and separating the main value streams is not practicable, at least in the short-medium term. Also, since throughput rate is determined by two shifting bottlenecks, POLCA and WLC are, plausibly, the only PPC techniques that could lead to lean benefits, quickly and without requiring substantial investments and/or changes to the actual layout. This will be the topic of the next Subsection.

### 4.6 Question #4: *«Are production mix and family routings relatively stable?»*

Typically, card-based PPC systems, such as POLCA or COBACABANA, can be simple yet effective means of controlling production (Germs and Riezebos, 2010; Thürer et al., 2014); nonetheless, these systems could also result much more difficult to be managed if production mix and family routings are not relatively stable. Specifically, to synchronise shared machines, one should use as many authorization cards as the number of alternative routings of the job-shop. Thus, if routings are not stable but change constantly, depending on the production mix required by the market, cards must be continuously readjusted, and their number rapidly grows and becomes unmanageable. Conversely, WLC does not need any cards, as it controls WIP by limiting the number of jobs that are admitted on the shop floor. This is made defining workload norms that have the advantage to be rather stable, with respect to variation of production mix, and easy to update. These considerations are summarised by Question #4.

To formulate an answer, we generated the detailed Current State Map (CSM) of the system collecting data directly from the shop floor. Because reproducing all the value streams on a single sheet was impossible, we made a specific CSM for each part family, as suggested in the M-VSM mapping tool by Marangoni et al. (2013). An example is given in Figure 3, which is relative to the value stream of family $F_1$.

Specifically, the main and linear flow represented on the map corresponds to the routing of $J_3$ (which is the one with the highest production volume) and most of the KPIs listed in the process boxes are relative to this specific value stream. These KPIs are: Cycle Time (CT), Changeover (CO), Changeover Probability P(CO), Defect Rate (DR) and the percentage of dedicated Time (dT). Conversely, only the Up Time (UT) and the Utilisation level (U) are global KPI, as they depend, solely, on the visited work centre.

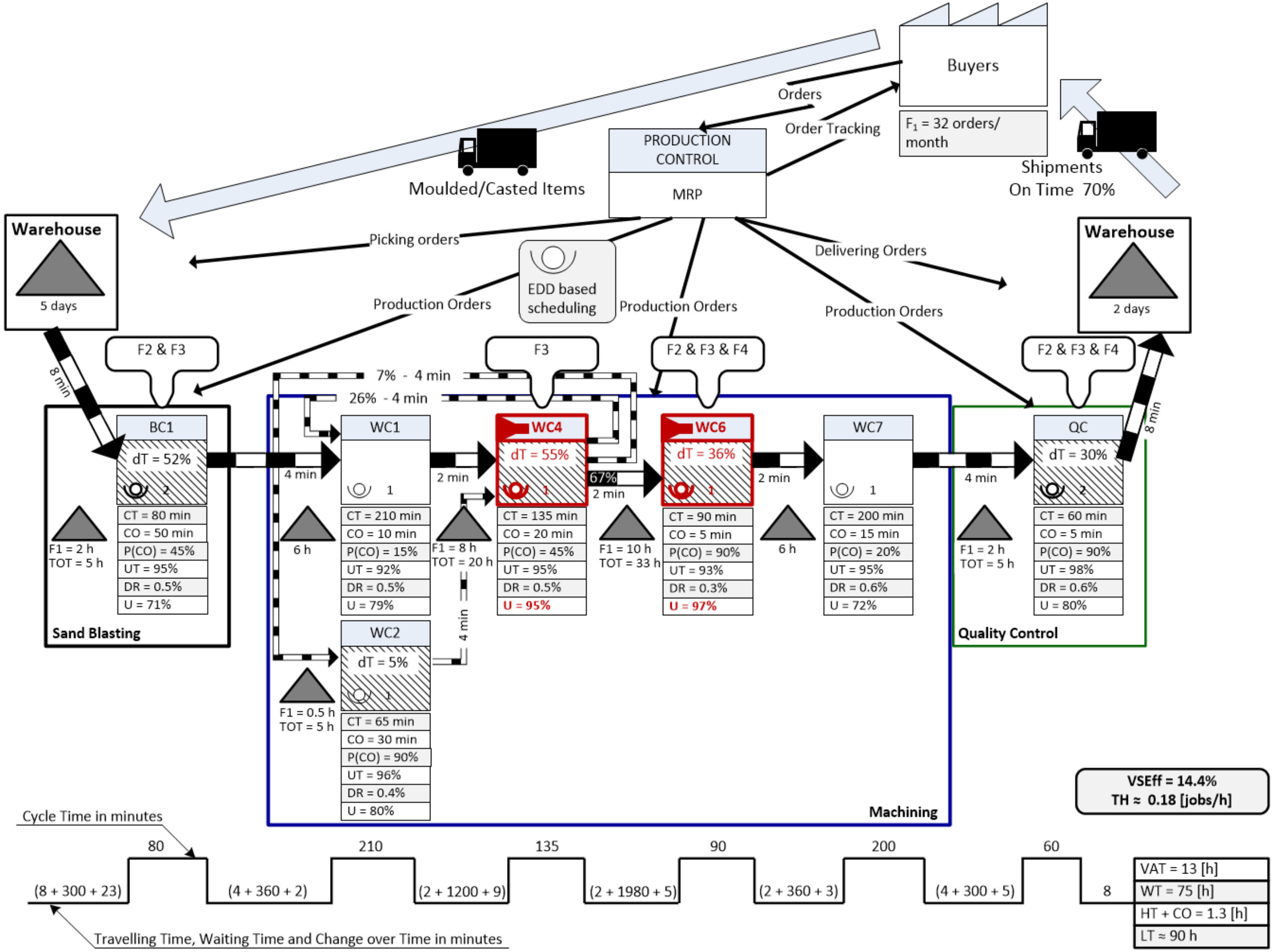


**Figure 3.** Family $F_1$ Current State Map

To increase the informative content, the current state map also shows:

- Secondary non-linear flows (with recirculation) and their flow rate;
- Shared machines - highlighted using a background layer - and the percentage of time dedicated to the family under analysis (dT);
- Interface icons (arrow shaped), with the list of all families visiting the same work centre;
- Queueing icons (triangle shaped), with the total waiting time subdivided by family;
- Bottleneck machines, highlighted in red and through a funnel shaped icon.

It is evident that routings of every product family (the situation for the other families is, indeed, similar to that of $F_1$) have a certain degree of recirculation, a fact that strongly discourages the implementation of POLCA, since authorization cards should be released at the job level and not at the family level. Thus, also the answer to Question #5 is “No” and, consequently, WLC was selected as the best PPC solution for I-SME. The design and the application of this PCC are described in the following Section.

# 5 Reconfiguring I-SME

As shown in the CSM of Figure 3, a Material Requirement Planning is executed to generate purchase and production orders needed to fulfil pending/booked orders and, possibly, to respect their due dates. Production orders are then forwarded to each department where detailed scheduling is based on the Earliest Due Date (EDD) sequencing rule. Unfortunately, by operating following this traditional push approach, performances are rather poor, as clearly indicated by the KPIs placed at the end of the time-line.

Note that some values slightly differ from those of Table 7; this is because, Table 7 reports rough average values, computed at the family level, whereas values of Figure 3 refer, exclusively, to the main value stream of the CSM and are based on real data collected on the shop floor.

Specifically, the Value Stream Efficiency (VSE) of 14.4%, computed as in (14), is very low and the Throughput rate of 0.18 [jobs/h], computed using the Little's Law as in (15) is ensured by an excessive level of WIP, equal to half the monthly customers' demand.

$$VSE_{F_i} = \frac{VAT_{F_i}}{LT_{F_i}} \tag{14}$$

$$TH_{F_i} = \frac{\sum_k J_{F_{i,k}}}{LT_{F_i}} = \frac{\sum_k \left( \frac{WIP_{F_{i,k}}}{CT_{F_{i,k}} + CO_{F_{i,k}}} \right)}{LT_{F_i}} \tag{15}$$

Where $J_{F_{i,k}}$ is the number of jobs of family $F_i$ that are queuing in front of work centre $k$.

As shown in (15), $J_{F_{i,k}}$ can be estimated taking the ratio of the WIP (expressed in unit of time) and of the processing time (i.e., cycle time plus change over time).

This situation causes long and highly variable lead times, an operating condition that makes it difficult to quote reliable delivery dates. Without a precise knowledge of its lead times, when contracting due dates with the customers, I-SME runs the risk to accept orders that are unlikely to be delivered on time. As shown on the map, the percentage of respected due dates is around 70% for $F_1$, and the situation is similar for all the other families.

Consequently, the following challenging goals were set

- 50% reduction of WIP;
- 40% reduction of LT;
- Due dates respect higher than 95%.

### 5.1 Lean improvements

Although MTO companies cannot easily implement lean tools, this is not an excuse for evading this step. At I-SME, since the production capacity was almost saturated, focused lean groups were formed with the aim to reduce machines' inefficiencies and time losses. The goal was to free up additional production capacity, especially at the bottleneck and at the shared machines, to facilitate the subsequent introduction of WLC. To this aim, autonomous maintenance activities and Single-Minute Exchange of Die (SMED) techniques were introduced to reduce minor stoppages and changeover times. Further, Visual Management and 5S techniques were implemented in every department to reduce confusion, eliminate useless or obsolete tools and to standardize material handling paths. These actions were particularly relevant in the warehouses and in the intermediate buffers, which were properly partitioned into areas dedicated to each family, to facilitate placing and identification of jobs, tools and materials.

### 5.2 WLC design and dimensioning

Lastly, the WLC system schematized in the Future State Map (FSM) of Figure 4, relative to family $F_1$, was designed and dimensioned, in accordance to the guidelines given by Bergamaschi et al. (1997). As it can be seen, I-SME synchronises and controls production following a pull approach in that picking and production orders are triggered by the acceptance and subsequent release of the orders pending in the PSP. Afterwards, released jobs move (in batches) on the shop floor following a push approach, as clearly shown by the black and white striped arrows connecting adjacent work centres. Note that, to underline that WIP levels are constantly controlled, the graphic of the above-mentioned arrows had been modified, compared to that of the standard push arrows (see Figure 3 for a comparison).

Also, to optimize the system, the following decisions were made.

Pre-Shop-Pull Management - Accepted customers' orders enter in the Pre-Shop-Pool (PSP), if the buyer has delivered casted or moulded items, and all necessary tools are available.

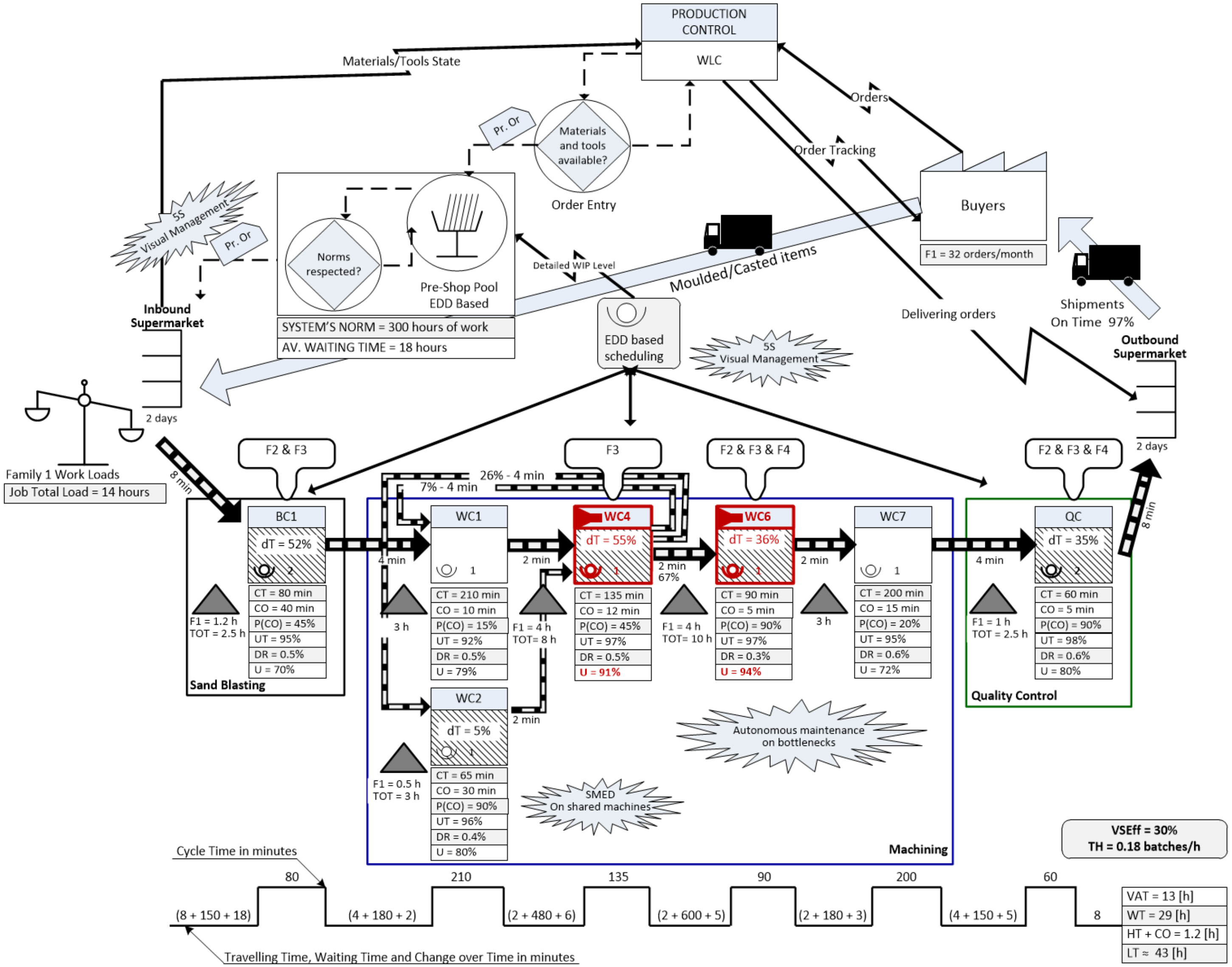


**Figure 4.** Family $F_1$ Future State Map

Order Entry Rules - To avoid starvations and possible production losses, the workload at the bottlenecks is always controlled. However, the work load of the system (regulating the overall WIP) is updated every three days, following a discrete timing convention approach, and it is compared to a single system's norm expressed as expected hours of work. If the work load of the system falls below this threshold limit, then pending orders waiting in the PSP are sorted based on their due dates and individually consider for release. Specifically, the first order is selected and its work load is added to that of the system. If the system's norm is not violated, then the job is released in the shop floor. This process is repeated for all the other jobs, until the systems' norm is not violated. In this regard, a crucial aspect concerns the way in which one considers the contribution (i.e., work load) of a job to the overall load of the system. For the sake of simplicity, we adopted an aggregate approach at the family level, that is: as soon as a job belonging to $F_i$ is released to production, the total load of the system is increased by a quantity $WL_{F_i} = \lceil \mathrm{VAT}_{\mathrm{F_i}} + \mathrm{CO}_{\mathrm{F_i}} \rceil$. For instance, from Table 7 it is easy to see that work loads are 14, 15, 12 and 13 [hours of work] respectively for family $F_1$, $F_2$, $F_3$ and $F_4$.

Another important decision concerned the definition of the system's norm. To this aim, we started from the upper bound suggested by Cigolini and Portioli-Staudacher (2002) and, next, we progressively reduced this quantity, until the throughput rate, for each family, did not fall below that of the original Push system equal to 0.18 [jobs/h] for family $F_1$ and, to 0.7 [jobs/h] overall. At the end of the optimization process, we obtained a system norm equal to 300 hours of work. Since the average work load of a job $\sum_{F_i}(\Lambda^{-1} \cdot \Lambda_{F_i} \cdot WL_{F_i})$ is equal to 13.5, the system's norm corresponds, roughly, to 22 jobs or, equivalently to 4 days of production.

Order Dispatching Rules - Once launched into production, jobs are pushed from a department to the following one. In case of queues, jobs are ordered according to their due date, but neither pre-emption nor batch splitting is admitted.

## 5.3 Preliminary results

Performances shown in the FSM of Figure 4 are the ones obtained after a full implementation (i.e., six months after going live) of WLC. All waiting times have dropped and, although transportation and processing times have remained unaltered, the total $LT_1$ in the shop floor (i.e., net of warehouse time) has decreased from 90 to 43 hours and, consequently, VSE has risen to 30%. All the other achievements are summarized, in average terms, in Table 8, which also shows the Coefficient of Variation (CV) of the total lead time before and after the implementation of WLC. As it can be seen, although the original goals have not been fully achieved yet, results are quite impressive. Indeed, WIP reduction and LTs contraction and stabilization made it possible to increase the service level offered to the customers that, at present, has risen from 72% to 93%. Thanks to WIP control, I-SME has obtained a clear knowledge of its manufacturing LTs, which are both shorter and less variable than before. Thus, I-SME can quote and/or negotiate the due date with the customers on a much stronger basis. This is certainly the most important result that we achieved.

**Table 8.** Average results after WLC implementation

| | **PUSH** | | **WLC** | | | |
|---|---|---|---|---|---|---|
| **Average WIP** | 30 jobs<br>400 hours of work | | 13 jobs<br>180 hours of work | | | |
| **DDs Respect** | 72% | | 93% | | | |
| | **Total LT** | **CV of LT** | **Shop Floor LT** | **Waiting Time at PSP** | **Total LT** | **CV of LT** |
| **$F_1$** | 90 [h] | 0.4 | 43 [h] | 18 [h] | 61 [h] | 0.1 |
| **$F_2$** | 110 [h] | 0.4 | 68 [h] | 20 [h] | 88 [h] | 0.2 |
| **$F_3$** | 70 [h] | 0.3 | 40 [h] | 15 [h] | 55 [h] | 0.1 |
| **$F_4$** | 60 [h] | 0.3 | 38 [h] | 15 [h] | 53 [h] | 0.1 |

# 6 Conclusions

This work belongs to the stream of research concerning lean application in manufacturing systems that are neither Make-To-Stock nor Assembly-To-Order. Specifically, the main focus is on Make-To-Order job-shop SMEs that are moving from push to pull, but where, due to different constraints, a pure lean and pull system cannot be easily achieved. Notwithstanding the economical relevance of job-shop SMEs, scientific works dealing with lean in these specific environments are rather scarce. This fact motivated our research that led to the definition of 2MTO, a new mapping tool, based on existing industrial engineering methods that have been improved and connected in a new way, to analyse and, eventually, to enhance performances of HVLV MTO job shops.

## 6.1 Novelty of the 2MTO

In a certain way, we could say that 2MTO is derived from VSM, but it has a much wider applicability. VSM (or similar mapping techniques), in fact, are the starting point of any lean initiative. However, when those techniques are applied to HVLV MTO companies, their analysis focuses, mostly, on a single product family, as it can be found in several papers in literature. In doing so, job-shops are assimilated to standard flow-shops, and this mono-dimensional approach ignores the distinctive features of a HVLV job-shop.

An alternative approach for HVLV job-shops concerns the use of hybrid PPCs; yet, these two streams of research (i.e., lean literature and hybrid PPCs) are not connected, as most of the hybrid PPCs are not included in the standard lean toolbox.

2MTO strengthen the connection between those streams of research. Generality and flexibility are, indeed, its main advantages, as 2MTO can be applied both to lean-friendly and non-lean-friendly environments:

- In case of lean-friendly environments (i.e., MTS or MTO companies that can be directly converted to pull) 2MTO simply suggests adopting well-known lean solutions and mapping techniques.
- In case of non-lean-friendly contexts, 2MTO suggests mapping the system at multiple levels of detail, to understand which lean technique, if any, can be applied to get local improvements, mostly at the machines’ level. Next, a set of straightforward numerical computations are used to select and dimension a suitable PPC technique (typically a hybrid one) to control WIP and reduce/stabilize lead times.

## 6.2 Discussion and future researches

Please note that, in case of non-lean-friendly environments, 2MTO requires the availability of many historical data and, possibly, of an ERP system. This should not be considered as a deterrent to the acceptance of 2MTO; indeed, the lack of information may be obviated by collecting data directly on the shop floor, following a simplified procedure. Although this step may be costly and time consuming, we believe that the future benefits could pay off the initial effort. In this regard, we note that our equations have been developed upon our industrial case, but the underlying principles of 2MTO are generic. In case of missing data, equations can be easily readapted to the case under analysis, according to the general principles of 2MTO and to the experience of the analyst.

2MTO was explained systematically, and a relevant industrial application followed, concerning an Italian SME operating in the precision mechanic sector. The analysis of the industrial application made it possible to identify two shifting bottlenecks and so, to achieve lean benefits, we agreed with the management of the company to control WIP by using WLC. Not to distort excessively the manufacturing system, we designed and developed a very simple WLC, based on a discrete timing convention approach (to release jobs) and on a workload aggregated at the total shop level. The implemented PPC is pretty simple; nonetheless, outstanding results have been achieved, the main one being an increase in respected due dates from 72 to 93%. This confirms the common belief that, once the company acquires greater knowledge of its average lead times, much higher on-time percentages can be achieved. However, since the throughput rate is regulated by two shifting bottlenecks, the use of specific norms on these machines should help to further reduce both lead times and WIP levels. The study of more advanced solutions, in fact, is already underway and will be implemented in the next future.

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