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Sustainable setup stream mapping (3SM): a systematic approach to lean sustainable manufacturing

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Abstract

This paper recommends a stepwise method, named sustainable-setup-stream-mapping (3SM), to improve manufacturing setup time and its sustainability impacts. The recommended method is developed based on an extensive literature review, in-depth explorative research in discrete manufacturing, and lean manufacturing tools: value stream mapping (VSM) and Single-Minute Exchange of Die (SMED). 3SM uses VSM in a novel way to break down setup operations, and employs SMED techniques to improve them. 3SM also recommends a list of criteria, for environmental, social, and economic pillars of sustainability, to assess the setup impacts against them within the setup workstation and in its relevant processes. This research implements 3SM in a real-life case, where the outcomes prove the practicality of 3SM and its improvements in setup times and sustainability criteria.

Given the lack of well-established methods to analyze sustainability in setup improvement, this research enhances the existing ideas around sustainable manufacturing to a more specific level, showing what/how sustainability criteria are influenced by setup activities/tasks at setup work station and factory-wide levels. This paper also expands the scope of SMED to sustainability improvement. The extended view of 3SM to setup and sustainability criteria, and its visual-analytical approach help managers to improve their operations more holistically.

Keywords: manufacturing setup, SMED, value stream mapping, sustainability, triple bottom line

1. Introduction

Flexibility, leanness, and responsiveness are widely recognized as key success factors for manufacturing systems (Jasti and Kodali 2015). The ability of a manufacturing process to setup and switch quickly from one product to another is vital for a flexible system (Martinez-Jurado and Moyano-Fuentes 2014; Panwar et al. 2015). Single-Minute Exchange of Die (SMED) is an advantageous technique to improve setup time, production lead time, and wastefulness (Negrão, Filho and Marodin 2017). It divides setup into internal activities, performed only when the machine is stopped, and external activities, carried out while the machine is in normal operation mode. SMED then tries to identify proper strategies for converting internal activities to external ones and streamlining both of them to minimize production halts.

SMED implementations have been reported and studied in various industries such as automotive (Cakmakci, 2009), food (Lozano et al. 2016), composite manufacturing (Ahmad and Soberi, 2018), aluminum profile factory (Baron and Ekincioglu, 2017), and cork stoppers production (Sousa et al. 2018). Notwithstanding its notable applications and benefits, SMED has barely moved beyond its operational boundaries. In particular, the SMED literature lacks thorough studies on sustainability aspects of setups, albeit it addresses some limited aspects of financial (Trovinger and Bohn 2005), manufacturing (Braglia, Frosolini, and Gallo 2017), energy (Belhadi, Touriki and El Fezazi 2018), and human (Baron and Ekincioglu 2017) factors in setup operations. From the manufacturing standpoint, although the manufacturing sustainability literature is quite extended and rich (Garetti and Taisch, 2012), the impacts of setup operations on sustainability are still largely neglected (see Section 2 for details).

Considering the sustainability's environmental, social, and economic aspects or pillars, coined as the triple bottom line - TBL (Elkington, 1998), the setup may have impacts on each of those three. In the environmental aspect, energy and water consumption (e.g. in pump manufacturing: Belhadi, Touriki and El Fezazi, 2018), and greenhouse gas emission (e.g. in the metalworking industry: Junior et al. 2018) are largely involved in setup operations. In the social aspect, setups usually engage both direct and indirect labor, and the production halt, during the production line/machine set up, may influence labor productivity and satisfaction (Trovinger and Bohn, 2005). Finally, the setup's economic impacts are more evident, due to the direct costs of equipment and labor (Allahverdi and Soroush, 2008).

In view of that, the nascent literature needs studies to explore the sustainability of setup operations and investigate how a commonly used technique such as SMED can include sustainability considerations. Therefore, this research:

(*1st*) explores the inclusion of sustainability pillars (i.e. environmental, social, and economic) in the SMED technique;

(*2nd*) recommends a method to
  - map and analyze the setup operations,
  - assess their impacts on the manufacturing system sustainability, and
  - improve the setup activities, times, and sustainability effects;

(*3rd*) tries out the applicability of the recommended method in a manufacturing case study.

The recommended method of this paper adapts the value stream mapping (VSM) approach (Serrano et al. 2009) to identify internal and external setup activities, and analyze their sustainability. VSM is widely used to visualize and improve operations by focusing on non-value-adding (known as waste) and value-adding activities, and trying to minimize and maximize them respectively. VSM in manufacturing typically leads to reduced production lead-time, inventories, and reworks (Lacerda et al. 2016). Therefore, the main outcome of this paper is a vigorous method, coined as Sustainable Setup Stream Mapping (3SM), to improve setup sustainability, while its activities are *(a)* well laid out in a value stream map, and *(b)* analyzed by an enhanced SMED technique, embedding environmental, social and economic pillars.

As a novel contribution to the literature, the 3SM visual and systematics approach improves setup operations in a more holistic way, compared to conventional SMED, in three ways:

(i) 3SM identifies setup improvement opportunities alongside their wider impacts on the whole manufacturing process. This is important since local optimizations (of setups) might

undermine the whole manufacturing performance if the manufacturing process is not seen as one system.

(ii) 3SM takes sustainability aspects of the setup operations into account while trying to improve the setup. Therefore, the improved setup offers improvements in the manufacturing process' environmental, social and economic pillars too.

(iii) 3SM implements a VSM based approach in the SMED to provide detail analysis of setup operations toward the above-mentioned contributions *(i)* and *(ii)*.

Details of the recommended 3SM method are provided and explained in Section 3, which follows the literature review of Section 2. The method is tried out in a home appliance manufacturing firm, and its details and outcomes are presented and discussed in Section 4. Finally, Section 5 provides the concluding remarks and the possible future developments.

2. Literature review

This section reviews the literature on SMED technique and sustainability as the main corresponding areas of this research.

2.1. SMED

Various approaches to conventional SMED have been applied in manufacturing processes (Silva and Filho 2019). Over the years, many studies have attempted to develop and expand the initial four-stage SMED technique, originally introduced by Shingo (1985) as shown in Figure 1.

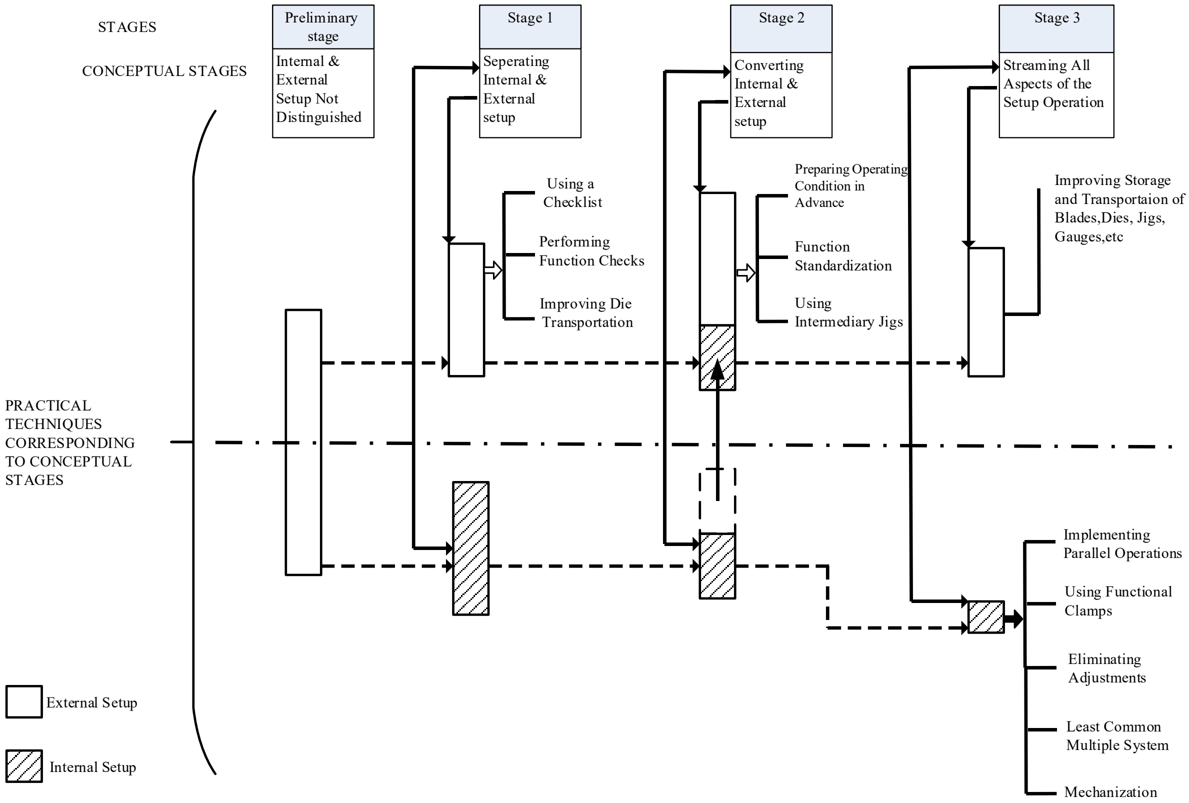


Figure 1. SMED conceptual stages and practical techniques (Shingo 1985)

Some studies have combined SMED with other concepts to improve setup activities and reduce setup time. Bevilacqua et al. (2015) generate an integrated setup reduction approach in a case study and apply SMED in combination with suppliers, inputs, process, outputs and customers, Kanban, 5S techniques, and total productive maintenance criteria to illustrate the importance of integrating lean practices to reduce variation in the setup time. They believe the standardization of setup tasks and the increased reliability in the material supply chain, in addition to reducing the setup meantime, can also reduce the standard deviation of the setup process time. Braglia, Frosolini, and Gallo (2017) present an integration of SMED with 5-Whys Analysis to illustrate not-optimized states from the setup prospect for reducing the effort and the cost of the SMED activity. Rosa et al. (2017) propose an approach to decrease setup times through the implementation of the SMED technique, complemented with other lean practices (5S, visual management, and standard work) to increase flexibility and productivity on the assembly line in a case study. Ekincioglu and Boran (2018) propose an integration between the fuzzy Taguchi method and the SMED approach to improve the setup, more than the conventional SMED approach.

Another theme in the SMED literature addresses the SMED impact on the firm's performance. Durmusoglu (1993) believes that implementing SMED plays an important role in reducing lot sizes and provides the ability to convert the job shop system to a cellular system. Cakmakci (2009) applies a statistical analysis method to investigate the relation between the SMED approach and equipment design. He demonstrates that SMED is a worthy approach for both manufacturing improvement and equipment/die design development. Lozano et al. (2017) measure the SMED impact on the mean time between failures and mean time to repair such failure with the cooperation of indicators such as global efficiency and overall equipment effectiveness. Martins et al. (2018) demonstrate how SMED can decrease the occurrence of errors in the equipment in the case of an electron beam machine. And more recently, Sousa et al. (2018) apply SMED to reduce the downtime caused by tool changes.

Some other papers focus on performing application strategies to extend and improve the implementation of conventional SMED. McIntosh et al. (2000) discuss the role of design to improve setup operations and maintenance performance. They show that design changes can to reduce the whole setup time including both internal and external times. Mukhopadhyay and Shanker (2005) create a SMED team and apply 5S, parallel execution, and standardization to eliminate wastes of setup operations and achieve the reduced setup time. Ferradás and Salonitis (2013) propose proper strategy definition and preparatory activities as the key steps for successful SMED implementation, which include project targets and timescale definition, appropriate team selection, roles and responsibilities dedication, and staff training. Braglia, Frosolini, and Gallo (2016) propose an approach, based on the SMED's duplication strategy, and investigate the feasibility of replicating the whole machine, fixture or equipment, to convert internal setup activities to external ones. Ahmad and Soberi (2018) apply tools such as the cause and effect and five whys analysis and introduce four strategies of activities elimination, conversion, combination, and simplification to extend the conventional SMED. Amrani and Ducq (2020) apply SMED and implement a number of improvements to reduce setup time including categorizing and performing the setup activities that need the same tool, modification of machine fixing parts, and initial preparation of the setup process. McIntosh et al (2007) analyze a retrospective improvement of changeover ability by altering the start time of the changeover task. In this way, a new interpretation of Shingo's SMED method is introduced, in which the improvement mechanism of task reallocation needs not to be accorded either dominance or precedence. Instead, improvement opportunities, at all stages of an overall initiative, should be assessed on merit.

2.2. Sustainability

The world commission on environment and development (WCED) defines sustainability and sustainable development as meeting 'the needs of the present generation without compromising the ability of future generations to meet their own needs' (WCED 1987). Consistent with that, the U.S department of commerce defines sustainable manufacturing as the 'creation of manufactured products which use processes that minimize negative environmental impacts, conserve energy and natural resources, are safe for employees, communities, and consumers and are economically sound' (DOC 2010).

Achieving sustainability in manufacturing requires an emphasis on environmental, economic, and social pillars (i.e. TBL), from pre-manufacturing, manufacturing, and use through post-use stages in the life-cycle (Faulkner and Badurdeen 2014). The importance of sustainability is evident for manufacturers (Presley, Meade, and Sarkis 2007) and several approaches have been performed to assess their sustainability state, identify and select sustainable solutions, and defeat the barriers for sustainability achievement (Eslami et al. 2020). Hartini and Ciptomulyono (2015) propose quantitative and qualitative analyses on the interrelationship between lean and sustainable manufacturing and their effects on performance. Cai et al. (2019) present an approach entitled lean energy-saving and emission reduction to assess and improve the environmental pillar of sustainability through eliminating waste of energy and industrial waste, energy-saving, and reducing hazardous gas emission. Kaswan and Rathi (2020) introduce the green lean six sigma model to improve sustainability TBL through reduction of hazardous gas emissions, waste, and manufacturing process variations, resulting in high quality, low cost, and eco-friendly products. Helleno, Moraes, and Simon (2017) propose sustainability criteria to assess manufacturing processes. They also provide an area classification according to TBL to help practitioners for analyzing and tracing the identified sustainability criteria (**Error! Reference source not found.**).

Error! Reference source not found.. Area classification according to TBL (adapted from Helleno, Moraes, and Simon 2017).

TBL	Area
Environmental pillar	Environmental management Environmental aspects Consumption Responsibility Product lifecycle analysis 3R's (Reduce, Reuse, Recycle) culture
Economic pillar	Cost management Corporative management Operational efficiency Products Operating results Suppliers Customers Infrastructure
Social pillar	Economic Satisfaction level Quality and Health Human resources Community

A more focused literature review of this paper has expanded the Helleno, Moraes, and Simon’s (2017) areas, and extracted an extensive number of sustainability criteria in manufacturing processes, as organized in Table 1. In the economic pillar, the sustainability criteria are grouped into two areas of cost management and operational efficiency. In the cost management area, costs criteria such as maintenance, energy, logistic, raw material, and labor are identified. In the operational efficiency area, the identified criteria include inventory, quality, flexibility, and delivery. The environmental pillar includes two areas of consumption and responsibility. In the consumption area, the criteria are identified as raw material consumption, energy consumption, and water consumption. In the responsibility area, the identified criteria include wasted material; wasted energy, and hazardous gas emission. In the social pillar, two main areas are identified: staff satisfaction and human resources. In the staff satisfaction area, the criteria are mainly around teamwork; motivation, and absenteeism. Finally, the human resources area mainly includes training and general policy.

Table 1: A summary literature review of identified sustainability criteria in manufacturing.

Area (criteria) / Author	Economic pillar		Environmental pillar		Social pillar	
	Cost management	**Operational efficiency**	**Consumption**	**Responsibility**	**Satisfaction level**	**Human resources**
Bhakar, Digalwar and Sangwan (2018)	Return on investment (ROI)	Management; Flexibility; Profit	Resources consumption	Waste management	Teamwork; Motivation; Employee involvement	Training
Brown, Amundson and Badurdeen (2014)			Raw material; Energy; Process water			
Cai et al (2019)			Energy Consumption	Waste management; Hazardous gas emission		
Caiado et al (2019)	Cost performance		Energy conservation; Energy consumption;	Environmental protection		Human capital development; Supplier relations
Caldera, Desha and Dawes (2017)			Energy consumption; Water consumption; Chemical material consumption	Wasted material/ energy; Chemical material; Hazardous gas emission		
Caldera, Desha and Dawes (2019)	Technology cost; Financial resources	Processes streamlining & standardization			Perceptions & attitudes of employees	Awareness; Training
Cherrafi et al (2016)	Waste elimination; Efficient use of resources			Waste elimination; Efficient use of resources	Management commitment; Employee involvement, Satisfying customer needs	
Cherrafi et al (2019)			Raw material consumption; Energy consumption;			
Choudhary et al (2019)			Raw material consumption; Energy consumption; Water consumption	Garbage; Hazardous gas emission; Biodiversity		
De et al (2018)	Maintenance cost	Inventory	Resource consumptions; Energy consumption	Waste management		Training
Faulkner and Badurdeen (2014)			Raw material consumption; Energy consumption; Process water consumption			
Garbie (2014)	Energy cost	Manufacturing strategies; Performance evaluation	Resources consumption	Hazardous gas emission; Water pollution; Land pollution; Waste management		Training; Human rights; Customer issues
Hartini and Ciptomulyono (2015)		Quality; Flexibility; Lead time; Inventory	Energy consumption; Process water consumption; Raw material consumption	Wasted material; Wasted energy		
Helleno, Mores and Simon (2017)	Operation cost	Effective cost; Stock cost	Energy consumption; Water consumption;	Hazardous gas emission; Waste segregation; Waste with traceable treatment	Absenteeism; Turn over	Benefits; Commission; Profit
Huang and Badurdeen (2018)	Operation energy cost; Direct labor cost; Product raw material cost Packaging related cost; Scrap cost; Water cost; Maintenance cost; Indirect labor cost;	Productivity	Raw material consumption; Energy consumption; Water consumption	Waste management; Hazardous gas emission		
Kaswan and Rathi (2020)		Inventory; Manufacturing process variations		Waste management; Hazardous gas emission	Teamwork; Customer satisfaction	Training
Latif et al (2017)			Energy consumption	Wasted material		General policy
Liu et al (2018)	Energy cost	Quality	Energy consumption; Raw material consumption	Wasted energy		
Mani et al (2014)			Raw material consumption; Energy consumption; Water consumption	Waste management; Hazardous gas emission		
Martínez and Javier (2016)	Operation cost	Lead time	Resource consumptions	Waste management; Hazardous gas emission	Employee commitment	Training
Ramos et al (2018)			Raw material consumption; Energy consumption; Water consumption	Hazardous gas emission; Reduce hazardous; Harmful and toxic materials; Solid waste		Training
Rauch et al (2015)	Logistic cost	Delivery time	Energy consumption	Wasted material; Wasted energy; Hazardous gas emission		
Singh, Olugu and Musa l (2016)	Manufacturing cost	Quality; Flexibility	Raw material consumption; Energy consumption; Water consumption	Waste management; Hazardous gas emission		
Souza and Alves (2017)		Quality of products and services; Overall equipment effectiveness (OEE); On-time delivery	Raw material consumption; Energy consumption; Water consumption			Training
Souza and Dekkers (2019)	Manufacturing cost		Resources consumptions;	Waste management	Motivation	Training
Tiwari, Sadeghi and Eseonu (2020)	Total cost			Hazardous gas emission	Absenteeism	
Torres et al (2019)		On-time delivery	Energy Consumption; Water consumption	Waste management; Hazardous gas emission	Employee involvement; Customer	Training

		satisfaction ; Absenteeism

As summarized in Table 1, although sustainability has been widely recognized in the manufacturing context, its specific relevance to the setup operations is partially addressed around some limited sustainability criteria only by few studies. Freeland, Leschke and Weiss (1990) focus on setup time and setup cost reduction programs to achieve zero cycle stock inventory. They explain that setup time must be considered in inventory ordering decisions, and setup time reduction has direct effects on opportunity cost. Trovinger and Bohn (2005) show the applicability of SMED in a variety of manufacturing processes and extend the SMED application in complicated manufacturing processes through applying modern information technology. Also, they assess the economic results of setup time reduction a including reduction in machine downtime and reduction in material handlers as economic benefits and increase in the number of line operators as an economic loss.

Baron and Ekincioglu (2017) show that in work environments with non-ergonomic setup activities, workers face different ergonomic risks and during the setup activities, muscle fatigue increases the setup times and risks of work accidents. They integrate the muscle fatigue assessment method into the traditional SMED approach to measure the ergonomic risks in setup activities and to reduce setup times. Brito et al. (2017) combine the SMED approach and ergonomics for reduction of setup in a turning production area. Junior et al. (2018) present a lean-green model based on the utilization of the SMED technique combined with carbon footprint to analyze the eco-efficiency of a machining center. Belhadi, Touriki and El Fezazi (2018) focus on preparation activities of internal setup operations and convert them to external ones, to reduce energy consumption and setup time, and finally increase operational and environmental performance. Overall, the outcomes of this paper's literature review reveal that there are limited researches on setup sustainability and its wider implications for the manufacturing processes. This further motivates the current research to investigate and analyze the sustainability and its specific TBL (environmental, social, and economic), affected by manufacturing setup operations.

3. Recommended Method: 3SM

Based on the gaps identified in the production setup literature (section 2), this paper recommends a method entitled "3SM" based on SMED, sustainability, and VSM method for sustainable manufacturing setup. The purpose of applying VSM is to highlight sources of waste and to identify improvement opportunities to eliminate them. VSM conventionally is used to map the production flow from the raw material into the arms of the customer, and the design flow from concept to launch. (Rother and Shook, 1999). It also tries to increase labor, machine, and material productivity (Seth and Gupta, 2005).

The proposed method of this paper helps to achieve a holistic view of setup operations, and analyze the sustainability impacts of the setup on the whole manufacturing process.

The recommended method tries to achieve three objectives:

- To visualize and analyze the setup process in detail, at the activity and specific task levels

- To factor in TBL, as the main pillars of sustainability to analyze the sustainability impacts of the setup operations
- To recommend holistic improvements in the setup operations in terms of:
  - IST, as a non-value operation itself and a major cause of the dependent production processes suspension,
  - total setup (IST+EST), as a non-value adding operation
  - TBL sustainability

Due to the dynamic nature of the business, setup operations, and TBL, the recommended method should be viewed as a continuous improvement tool, than a one-off project. To explain its recommended method, this paper first defines the metrics, which improvement actions are defined based on them, and the achievements are measured against them (sub-Section 3.1). In view of them, then details of the analysis and improvement steps are explained in detail (sub-Section 3.2).

3.1 Performance criteria

3.1.1 Setup time

The conventional SMED method focuses on setup activities and tries to reduce setup time (as the main performance criterion) through four conceptual stages (as shown in Figure 1). Accordingly, the recommended 3SM, as a visual systematic method, maps all setup operations at activity and task levels on the timeline, to *(a)* provide a detailed analysis for distinguishing IST and EST, *(b)* converting IST to EST, and *(c)* streamlining both of them.

3.1.2 Sustainability criteria

3SM's sustainability performance criteria mainly follow the areas extracted from the literature in Section 2 and Table 2, for each environmental, social and economic pillar, as follows.

Environmental criteria are typically defined around energy consumption, water, pollution, and material consumption/waste/recycling. In the energy section, over and above focusing on using sustainable and renewable sources, the total energy required by the setup operations should be managed and improved too. In the water section, both total water consumption and also the share of reclaimed water (wherever possible) are considered. In the material section, due to the importance of prudent use of non-renewable resources, the waste of raw material during the setup process and inventory waste that occur through excess inventory handling to downstream manufacturing process during setup operations, are considered as sustainability criteria in environmental assessment. Also, assessing how much of the consumed material during the setup process is recycled-reused, the criteria can assess the share of recyclable material out of the total required material for the setup. The performance criteria above are summarized in Table 2.

Social criteria usually involve an extensive range of factors which may vary case by case. In general, the criteria which are related to the wellbeing of employees and the community are considered. Given that setup in one manufacturing process stops its manufacturing operations, and possibly the production in other relevant processes, it makes some operators jobless for a few or several hours and waste of operator occurs. This may affect the employees' morale and satisfaction. The more interruption the setup causes for manufacturing, in one or multiple manufacturing processes, the more chance of dissatisfaction among the employees.

On the positive side, setup operations may encourage teamwork within the setup process, between the setup manufacturing station operators and the setup specialist operators, and also other operators (of other manufacturing processes who come to help to finish it quickly). In this regard, performing training courses will increase the number of skilled operators to achieve efficient teamwork. Table 2 shows the proposed setup social criteria.

Economic criteria are usually well recorded in organizations and retrievable from the finance and accounting measures and reports. Direct economic criteria are linked or refer to the immediate setup operations, and indirect criteria are the ones that occur in other manufacturing processes or the general overhead cost. The direct criteria include operator, material, and energy as the main building blocks of any operation (including setup) cost. Keeping inventory in the setup workstation to keep production running during the setup and in some cases, their waste during handling to downstream manufacturing process are also added to the direct cost. Cost elements of direct criteria are typically straightforward to estimate (e.g. 100 ml of lubricant type X = $Y). However, the indirect criteria are more complicated to specify and measure and may be limited to some rough estimations. A summary of economic criteria is listed in Table 2.

It should be noted that the criteria of Table 2 are not exhaustive, and their applicability may vary for different manufacturing processes and setup operations.

Table 2. Setup sustainability criteria.

TBL	Criteria
Environmental pillar	Energy consumption (kwh) Material disposal (%) Hazardous gas emission (HGR) (M3) Water consumption (lit) Inventory waste in handling (%)
Social pillar	Health & Safety Operator waste during setup time (mh) Teamwork (m) Skilled operator (%)
Economic pillar	Direct criteria: Cost of wasted material during set up ($) Cost of supplementary material (e.g. lubricants and adhesive) ($) Cost of manpower, involved in set up operations ($) Cost of energy consumption during setup ($) Inventory: cycle inventory + buffer inventory (in case setup takes longer time), to keep manufacturing run during setup time (pcs) Handling cost: moving the molds, fixtures, and other equipment from/to their storage area to/from the setup location ($) Cost of inventory waste ($) Cost of operator waste during setup time ($) Indirect criteria: Extra inventory, kept by the connected manufacturing stages, because of this setup Overhead cost (contribution of this setup to indirect cost like admin, management, security…)

3.2 Stepwise procedure

Details of the recommended method of this paper are elaborated in this section. The method is also summarized in Figure 2.

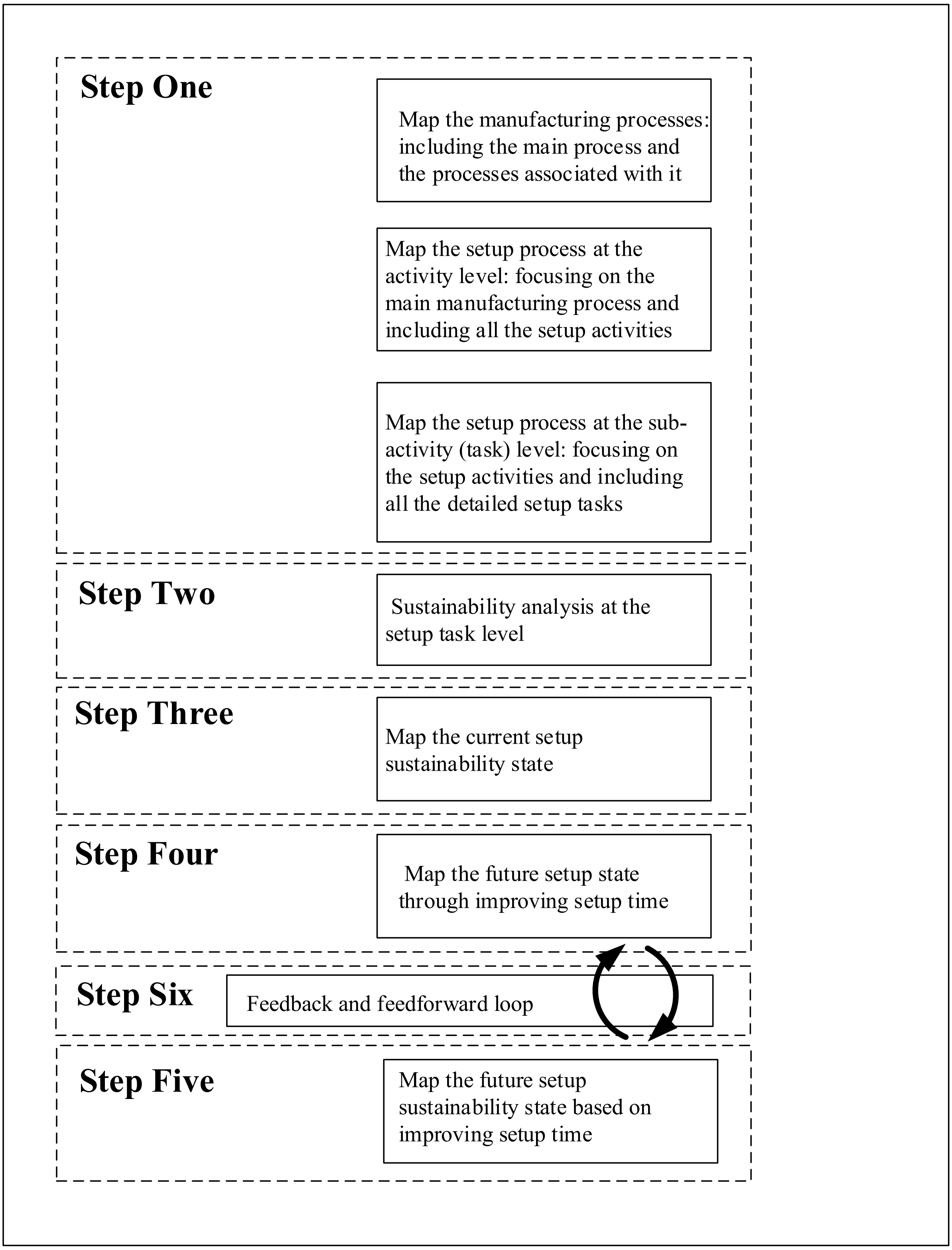


Figure 2. The main steps and actions of the recommended 3SM method

Step One: Multi-level mapping of the current setup state

To present and analyze a specific setup operation, the process mapping is carried out at three levels, as illustrated in

and explained below:

- Level I: The position of the manufacturing process (or the work station) that hosts the under-study setup is identified across the value stream map of all relevant manufacturing processes. This is called mainstream map, as shown in
-
-
- a.
- Level II: All activities of the under-study setup are identified in a focused setup stream map, as shown in
-
-
- b.
- Level III: Detailed tasks of each activity of the under-study setup (as identified in level II) are specified in a further focused setup stream map (
-
-
- c).

Mapping the production processes, at level I, demonstrates connections between the setup workstation and the rest of the manufacturing processes. Key data such as cycle time, setup time, operational and labor capacities, inventory level, inter-station material handling method, and Bill of Material (BoM)/Material Requirement Planning (MRP) data are needed to support the process map at level I. A full view of the manufacturing processes at level I helps analyzing the effects of the setup operation (including its sustainability effects), beyond its work station. Mapping the setup activities and their detailed tasks, at levels II and III, helps to comprehend the internal and external setup activities and their associated tasks. The setup activities and tasks are mainly measured in terms of time. This is quite essential for any improvement action in terms of separating internal and external activities/tasks, transferring the internal activities/tasks to external ones, streamlining them, and assessing their sustainability impacts. Consistent with that, breaking activities, to their constituent tasks (i.e. moving from level II to level III), should be done up to the point where their timings can be estimated accurately and shifting/eliminating them can be realized. This may vary for different activities and tasks. For example, while most activities are not needed to be broken down into small moves of the operators or equipment, some can benefit from that level of detail, where more internal tasks can be externalized. Table 3 exemplifies too much vs. too little broken-down activities, where the former one is unnecessary and the latter one is inadequate and unhelpful.

Table 3. Breaking down setup activity into its tasks: an example of too much vs. too little details.

Activity: Releasing the existing die from the machine

Tasks:	
Too much	*Too little*
Moving toward the machine Looking at the die and its position in the machine Identifying locations of the sections which should be disjointed Taking the required tools near the machine Taking the wrench size 12 Moving the wrench to the front nut . . .	Release the connections Remove the die

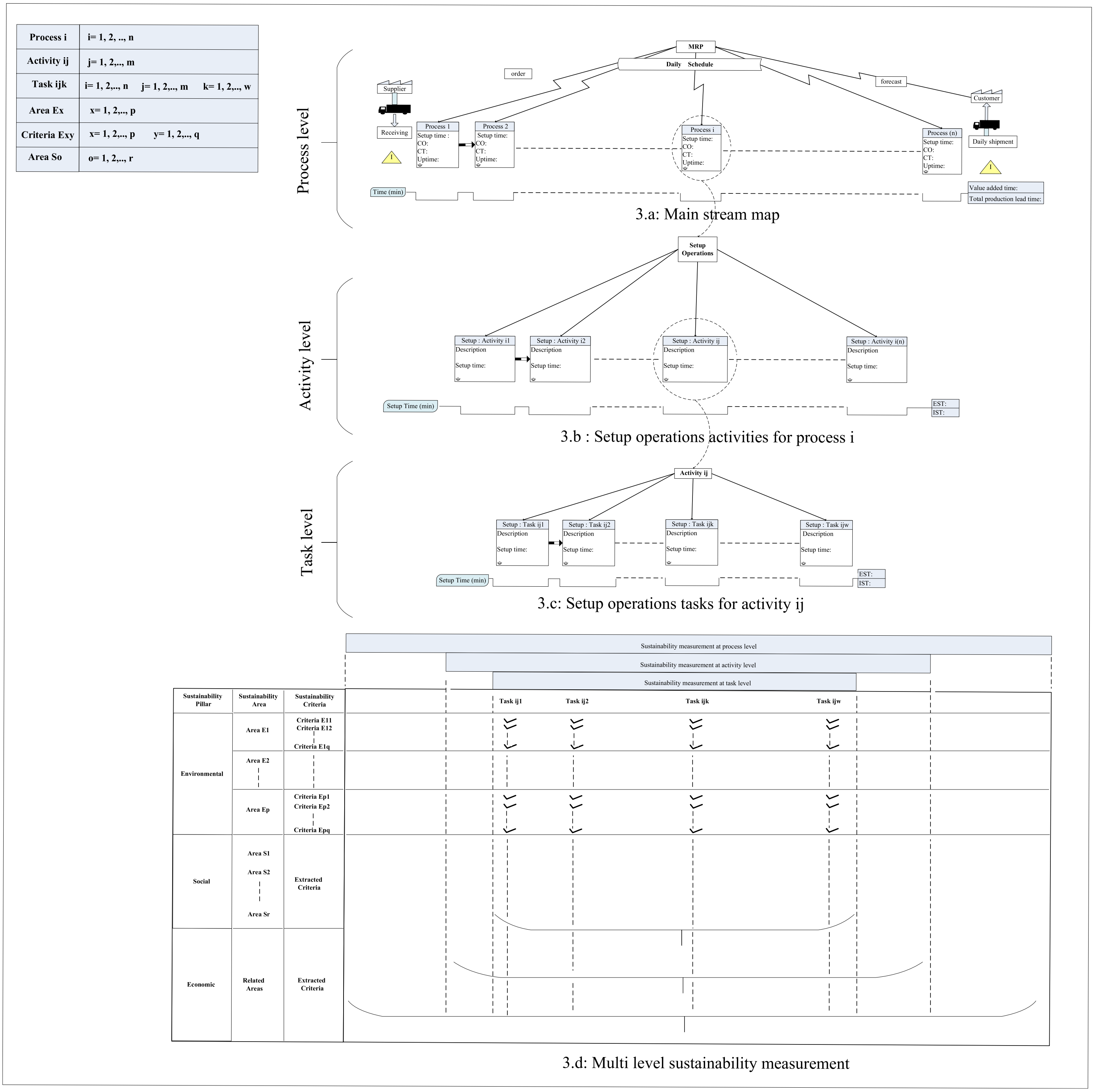


Figure 3: The stepwise procedure of the proposed approach

Step Two: Sustainability analysis at the setup task level

Going through the detailed setup tasks of step one, it should be identified which of the sustainability criteria (of Table 2) are applicable to them. Obviously, each task may involve only some of those criteria (for example a task may involve only material waste but not harmful gases). Similarly, multiple tasks may be collectively linked to one criterion (for example a number of tasks on releasing different parts of a die together engage operators in teamwork – i.e. a social criterion).

Step Three: Map the current setup sustainability state

In this step, the sustainability effects of each setup task on other relevant manufacturing processes (as mapped in step one) are identified and measured (as exemplified in Figure 3.d). This measurement is typically complex and should not be simplified and rushed. For example finding how much extra inventory is kept in manufacturing process *X*, due to the setup operations in manufacturing process *Y*, may need input data from the factory information systems (e.g. ERP or MRP) and knowledgeable people/managers of the relevant manufacturing processes. More qualitative criteria such as staff satisfaction or teamwork may need even further research to assure valid results. The success of this step also largely depends on well-defined and clearly formulated sustainability criteria. Section 3.1 provides a number of criteria for each sustainability pillar, however, the scope and details of them should be specified based on the real-life situation of the manufacturing and setup activities/tasks in practice.

If done properly, the measurements of this step can provide a broader view of the setup sustainability effects, and lead to a more holistic improvement in the setup operations.

Step Four: Map the future setup state through improving setup time

Considering the stepwise procedure of the proposed approach in Figures (3.a, 3.b, and 3.c), the improvements in setup times follow the SMED strategies such as duplication, parallel execution, and standardization (Shingo 1985; Braglia, Frosolini, and Gallo 2016) to convert IST to EST and streamlining them. Changes in internal and external setup tasks may have positive and also negative impacts on sustainability criteria too. For example, although shrinking the internal tasks may reduce IST and inventory, it may lead to some external tasks which consume more energy and cause air pollution. These effects should be measured and considered for the sustainability criteria improvements in step Five.

Step Five: Map the future setup sustainability state based on improving setup time

Sustainability criteria improvement does not follow a universal formula, and each criterion in each manufacturing process needs a specialist team to work on it. Some general techniques such as brainstorming, cause-and-effect analysis, and design of experiment are certainly useful, but each of them needs to be employed in the specific context of the setup operations and its relevant manufacturing processes. This research employs a stepwise procedure to present the achieved improvements in TBL, as is shown in Figure 3.d.

The recommended improvements in this step may encourage further improvement in setup times or adversely affect them. These effects should inform the earlier IST and EST calculations in a feedback loop.

Step Six: Feedback and feedforward loops

Changes in setup times (Step Four) and Sustainability criteria (Step Five) may have impacts on each other. These may need to go through a number of forward and backwards loops until the associated parties agree on an acceptable trade-off among the time and sustainability criteria. It is important to bear in mind that in practice it is not plausible to achieve an optimum level for all criteria. The relative importance of time and sustainability criteria determines the ultimate solution in the feedforward and feedback loops between Steps Four and Five. In some cases, the manufacturing decision-makers may come up with a number of alternative ideas and solutions.

4. Implementation of the 3SM method in a real-life case

This paper tries out the implementation of its proposed 3SM method in a cabinet foaming process of a refrigerator factory in a home appliance firm. This section first introduces the cabinet foaming process in brief. It, then, goes through the machine setup operations of the process. Finally, the 3SM steps and their implementation in the cabinet foaming process setup are explained.

4.1 Refrigerator manufacturing: the cabinet foaming process

This factory is active in the field of home appliances and produces a range of white goods. The proposed 3SM method is applied for the changeover of two different models of refrigerators in the cabinet foaming process, which is recognized as one of the important manufacturing processes in the factory. This process includes series of operations that provide the insulation of the refrigerator cabinet with foam injection and consists of three stages including assembly operations before foaming, foaming operations, and assembly operations after foaming. In the foaming operations as the main part of this process, firstly cabinet inters preheating zone to be appropriately heated and become ready for foam injection, then enters to the foam injection machine which includes; cabinet fixtures, cabinet die, injection housing, injection head, injection hoses, control panel, and other related components. It is remarkable that there are seven operational foam injection machines to increase the manufacturing capacity of this section and being balanced with the cycle time of other manufacturing processes. The injection foam used in this process is rigid polyurethane foam which is composed of three main materials including; Polyol; Cyclopentane and Methylene diphenyl diisocyanate. In continue, after fixing the cabinet in the foam injection machine with the aid of die and fixture, the foam is injected in the volume between inside and outside walls of the cabinet through pumps, hoses, and injection head, then foam starts rising and curing. In this machine, the die is placed inside the cabinet and is fixed to the inner polymeric body of the cabinet to protect its form and prevent the deformation of it against the pressure of rising foam, and helps to the homogenous distribution of foam in the above-defined volume of the cabinet. Also, there are heating elements inside the die that help to maintain the proper temperature of inner polymeric body of the cabinet during the foaming process. After foaming, the cabinet is sent to the next stage for assembly operations.

4.2 Setup process in the cabinet foaming machine

The setup process in the cabinet foaming machine consists of 11 activities and each activity is broken down into its related tasks. These activities and tasks are replicated for all seven cabinet foaming machines of the cabinet foaming room. In the following steps, setup activities and tasks are described briefly.

Setup activity 1: Release the previous die from the foaming machine and take the die to the standby room. The injection housing, electrical and pneumatic connectors are released, and then the die is removed from the foaming machine and transferred to the standby room.

Setup activity 2: Move out the previous die set (die and fixture) from the standby room. The die set is transferred from the standby room (located on the first floor) by the carrier to the lifter platform. After grounding the lifter, the die set is picked up by the forklift and placed on the wooden base.

Setup activity 3: Release the previous die from the fixture. Pins, side wing, lower base, electrical sensor, nuts, and protection bar are disassembled from the die and the rail of fixture is released from the die.

Setup activity 4: Release the new die from the mold rack and replace it with the previous die in the die rack. The new die is picked up from the rack using the forklift and is placed on the ground. Then, the cover of the new die is taken out and the new die is picked up using the forklift. In continue, the bolts are opened for releasing the new die from the die holder and the die holder is pulled out. In the next step, the previous die is placed inside the die holder and installed, covered, and picked up using the forklift, and finally placed in the die rack**.**

Setup activity 5: Place the new die inside the die fixture. Firstly, the fixture is placed on a wooden base. In continue, the connecting pins of the die are checked, then, the die is placed inside the fixture and the fixture is locked on the die.

Setup activity 6: Install the new die in the fixture. The protection bar, nuts, electrical sensor, lower base, side wing, and Pins are installed in the die. Then, the distance between the top wall of the fixture and the die is adjusted.

Setup activity 7: Transfer the new die set into the standby room. The new mold set is placed on the platform using the forklift and is locked to the lifter on the platform. Then, the die set is transferred to the standby room, and in continue, it is placed in the final position by the carrier in the standby room.

Setup activity 8: Heat up the new die. The die heating is done through a heating fan in the standby room.

Setup activity 9: Place and install the die into the foaming machine. The injection housing is installed, then the new die is transferred to the foaming machine and the electrical and pneumatic connectors are installed.

Setup activity 10: Clean the die set and foaming machine fixture. The die set and cabinet fixture are cleaned to remove any dirt or dust from the surfaces.

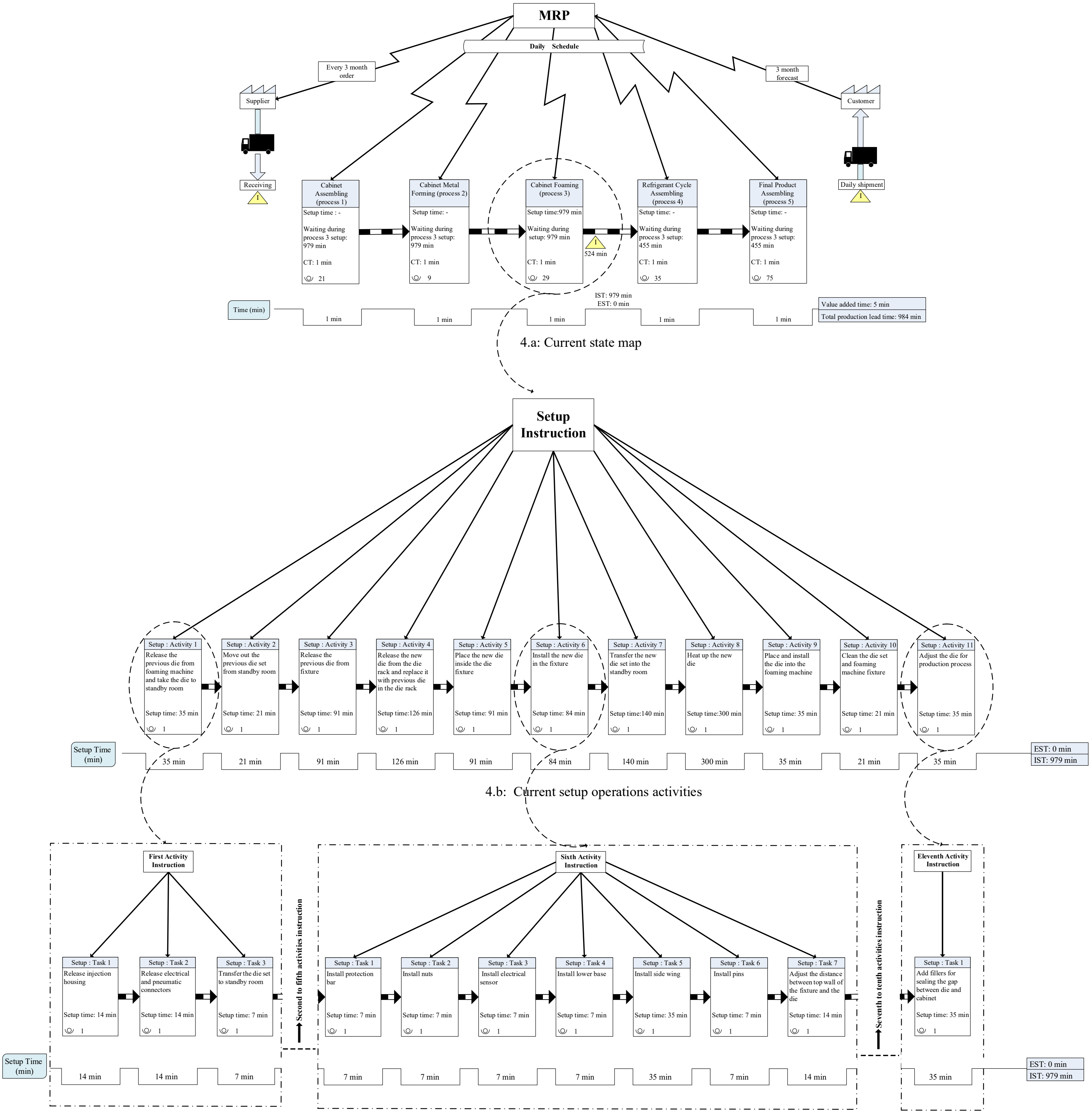
Setup activity 11: Adjust the die for the manufacturing process. According to the installation of the die to its fixture and the mold coordinate in the cabinet foaming machine, in some areas on the die surface, fillers are added for sealing the gap between die and cabinet and avoiding any deformation on the cabinet internal surface that may appear after the foam injection process.

4.3 Implementing 3SM

Following the 3SM procedure (Figure 2), its main steps in the cabinet foaming process setup case are implemented as follows.

Step one - cabinet foaming machine setup: multi-level mapping of the current setup state

Firstly, to have an overview of the existing situation of the product value stream, the current state map is drawn to illustrate value-added time and total manufacturing lead time in the refrigerator manufacturing process. The current state map consists of five manufacturing processes including cabinet assembling, cabinet metal forming, cabinet foaming, refrigerant cycle assembling, and final product assembling. As it is shown in **Error! Reference source not found.**.a, this paper focuses on the cabinet foaming machine setup process. All activities of the cabinet foaming machine setup are then mapped on a timeline (**Error! Reference source not found.**.b), where IST and EST, and operator allocations are identified. To distinguish between IST and EST visually, this paper demonstrates the external setup activity data box and EST of timeline, with a dashed line. For further analysis of the existing setup process, the setup activities are broken into their tasks. In this example, the task level map is provided for three setup activities including first, sixth and eleventh, as shown in **Error! Reference source not found.**.c.



4.a: Current state map

4.b: Current setup operations activities

4.c: Current setup operations tasks

Figure 4: Multi-level current map

Step two - cabinet foaming machine setup: sustainability analysis at the setup task level

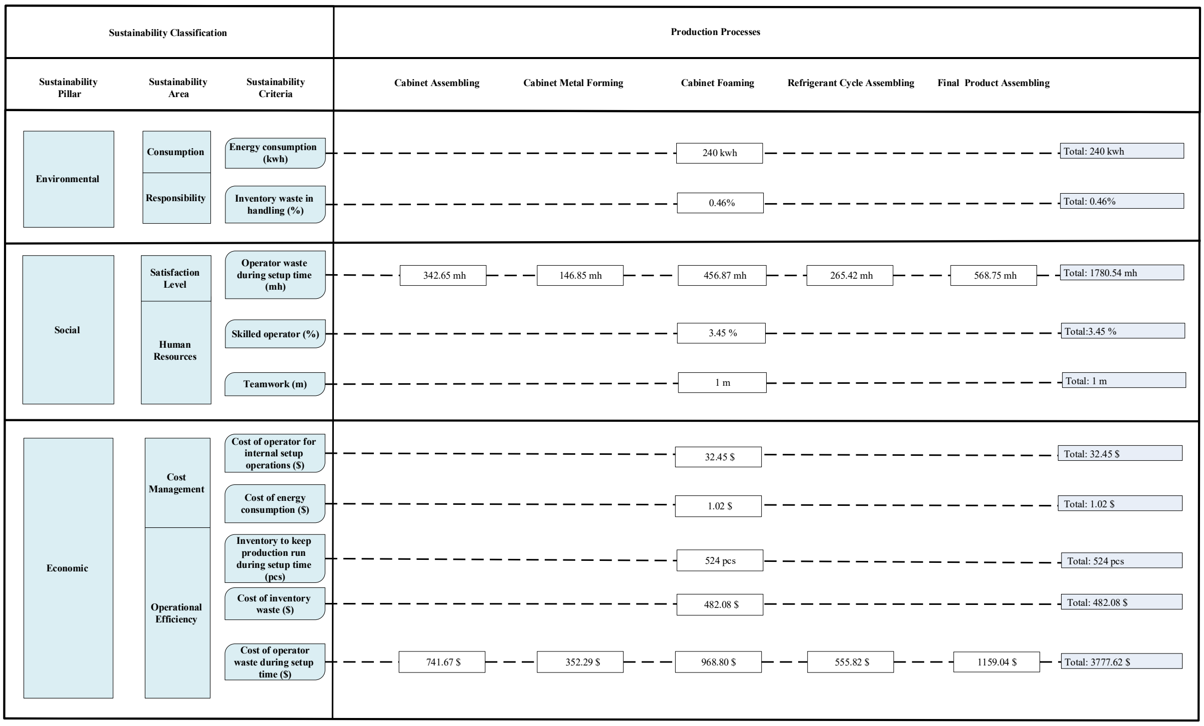
Based on the sustainability criteria, recommended earlier in Table 3, relevant TBL criteria are identified for this case, as presented in Table 5.

Table 4. Sustainability structure in the case study, including the pillars, areas, and relevant criteria.

TBL	Area	Criteria
Environmental pillar	Consumption	Energy consumption (kwh)
	Responsibility	Inventory waste in handling (%)
Social pillar	Satisfaction level	Operator waste during setup time (mh)
	Human resources	Skilled operator (%)
		Teamwork (m)
Economic pillar	Cost management	Cost of operator for internal setup operations ($)
		Cost of energy consumption ($)
	Operational efficiency	Inventory to keep production run during setup time (pcs)
		Cost of inventory waste ($)
		Cost of operator waste during setup time ($)

Step three - cabinet foaming machine setup: map the current setup sustainability state

In this step, sustainability criteria that are introduced in Table 4, are measured and applied in the specified areas and pillars to present the current setup sustainability state. The measured criteria in **Error! Reference source not found.** present an assessment of TBL, before applying the improvements



Sustainability Classification			Production Processes					
Sustainability Pillar	Sustainability Area	Sustainability Criteria	Cabinet Assembling	Cabinet Metal Forming	Cabinet Foaming	Refrigerant Cycle Assembling	Final Product Assembling	
Environmental	Consumption	Energy consumption (kwh)			240 kwh			Total: 240 kwh
	Responsibility	Inventory waste in handling (%)			0.46%			Total: 0.46%
Social	Satisfaction Level	Operator waste during setup time (mh)	342.65 mh	146.85 mh	456.87 mh	265.42 mh	568.75 mh	Total: 1780.54 mh
	Human Resources	Skilled operator (%)			3.45 %			Total:3.45 %
		Teamwork (m)			1 m			Total: 1 m
Economic	Cost Management	Cost of operator for internal setup operations ($)			32.45 $			Total: 32.45 $
		Cost of energy consumption ($)			1.02 $			Total: 1.02 $
	Operational Efficiency	Inventory to keep production run during setup time (pcs)			524 pcs			Total: 524 pcs
		Cost of inventory waste ($)			482.08 $			Total: 482.08 $
		Cost of operator waste during setup time ($)	741.67 $	352.29 $	968.80 $	555.82 $	1159.04 $	Total: 3777.62 $

Figure 5: Current setup sustainability state

As explained in Section 3, depending on the manufacturing system, setup time can impact sustainability assessment in whole manufacturing processes in a company. For example, in this case study, the setup operations cause operator waste in all manufacturing processes, and impact on satisfaction level and operational efficiency areas, as is shown in **Error! Reference source not found.**. A collective review of the presented data in **Error! Reference source not found.**.c and **Error! Reference source not found.** shows one of the main benefits of 3SM. Whereas, detail analysis of the setup tasks indicates the effect of each task on sustainability, the sustainability assessment clarifies the potential improvement opportunities in the setup operations. For example, using one person in a setup task demonstrates its effects on setup time length and simultaneously shows its effects on sustainability criteria such as teamwork, operator waste, costs, and inventory.

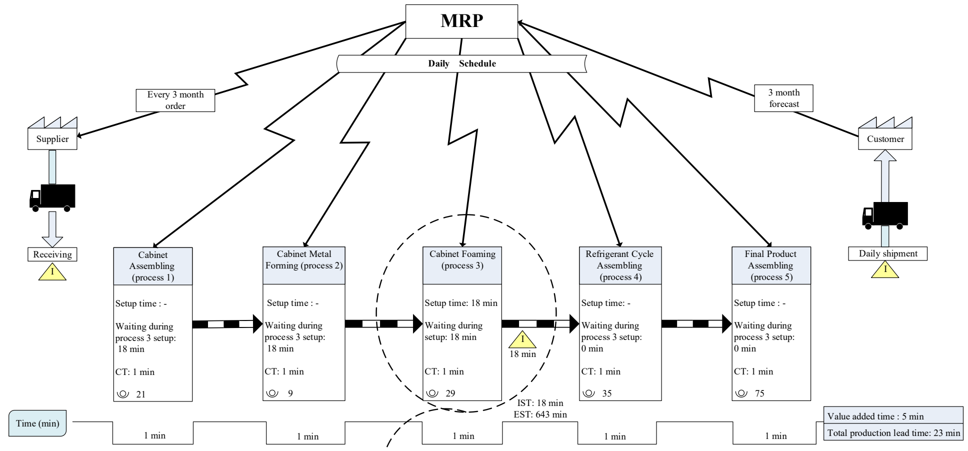
Step four - cabinet foaming machine setup: map the future setup state through improving setup time

The thorough process maps in step one, and sustainability assessment in step three, facilitate SMED improvement strategies such as duplication, parallel execution, and standardization to improve the setup process.

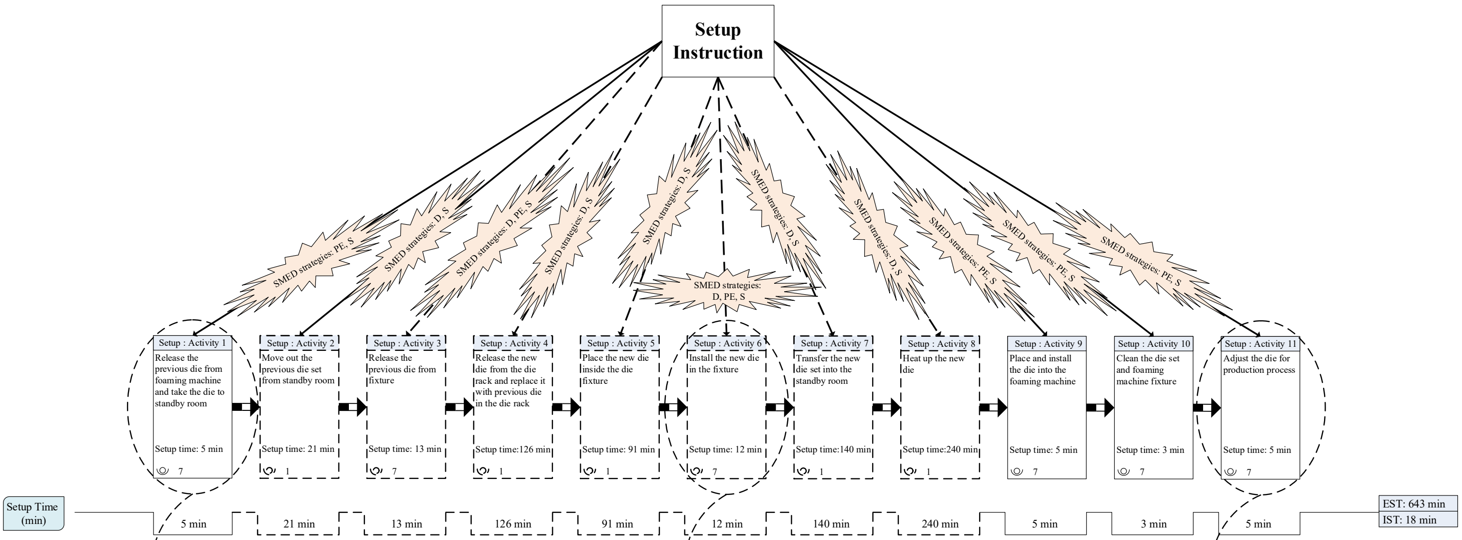
For implementing duplication strategy, based on the number of foaming machines, seven more fixtures are made in addition to the existing fixtures in the die set. It is remarkable that duplicating fixtures leads to externalizing series of setup activities and tasks (the activities and tasks that are dependent on the presence of fixtures out of production operational area, as they are shown in the improved process maps (**Error! Reference source not found.**.a, 6.b and 6.c).

For applying parallel execution strategy in the setup process, a training course is planned and performed to increase the number of skilled operators and to provide the ability for doing the setup tasks in parallel in the specified activities (activities 1, 3, 6, 9, 10 and 11).In this regard, based on the number of foaming machines, seven operators are trained to do the mentioned activities in parallel. It is remarkable that applying a parallel strategy leads to significant reduction in setup time which is explained in section 4.4.

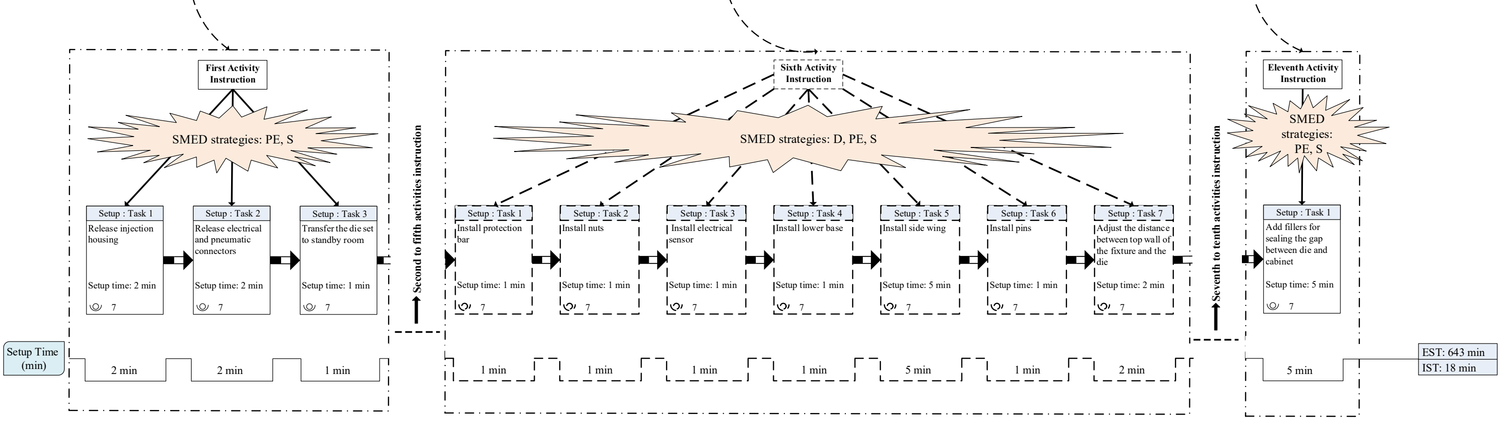
Standardization strategy is then applied to setup activities, tasks, IST, EST, and required resources such as the number of skilled operators, tools, and equipment. It helps the practitioners to clarify all steps of the setup process and prevents the diversity of time and methods in performing setup operations, and finally leads to define a standard method and standard time for the whole setup process. Furthermore, implementing this strategy helps the planning department to assess the machine's available time and the manufacturing capacity.



6.a: Future state map



6.b: Future setup operations activities



6.c: Future setup operations tasks

Figure 6: Multi-level future map

Step five - cabinet foaming machine setup: map the future setup sustainability state based on improving setup time

Based upon the improvements made in the setup process in step four, changes in the sustainability criteria across the relevant manufacturing process are measured. Then, through a number of feedback and feedforward iterations (step six) the improved setup sustainability state is resulted, as mapped in **Error! Reference source not found.**.

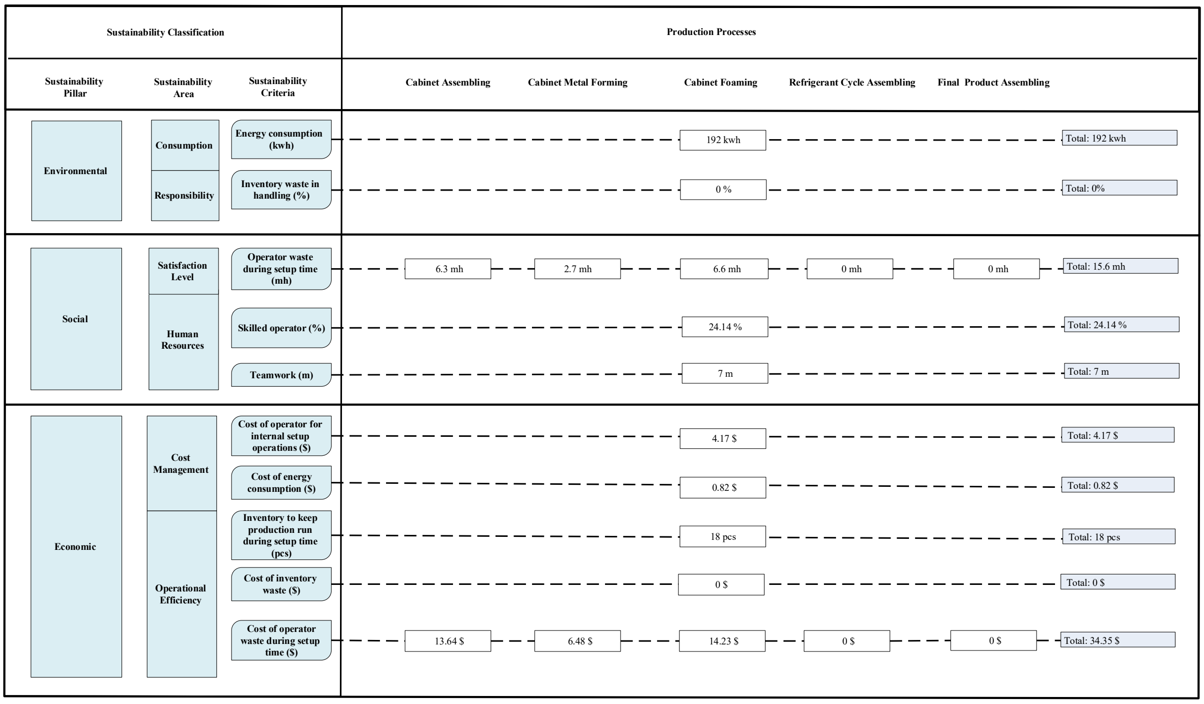


Figure 7: Future setup sustainability state

4.4 Results

Results of the 3SM application in the case study above are presented and reviewed in two main areas of setup time/improvements and sustainability performance improvements. For setup time, a reduction of 85.7% is achieved in activities 1, 3, 6, 9, 10, and 11 (**Error! Reference source not found.**a). These significant improvements are the results of implementing a parallel execution strategy, where seven people, instead of one person, execute the tasks in parallel in each one of those activities The setup activity 8 heats the die as one of the externalized activities. In the improved state, the die set heating is done when the foaming machine is running in the production process. In this regard, the cabinet foaming room temperature during the production process increases the speed of die set heating in the standby room which is placed on top of cabinet foaming machines and leads to 20% setup time reduction in activity 8. The setup times of activities 2, 4, 5, and 7 are not reduced directly because of machine and equipment limitations in transferring die sets. These activities are, however, externalized, along with activities 3, 6, and 8. The externalization results are shown in **Error! Reference source not found.**b. It shows how a duplication strategy can be useful in externalizing setup activities. In particular, duplicating fixtures of the die set allows doing the mentioned setup activities out of machine area, during the time that foaming machine is in running mode.

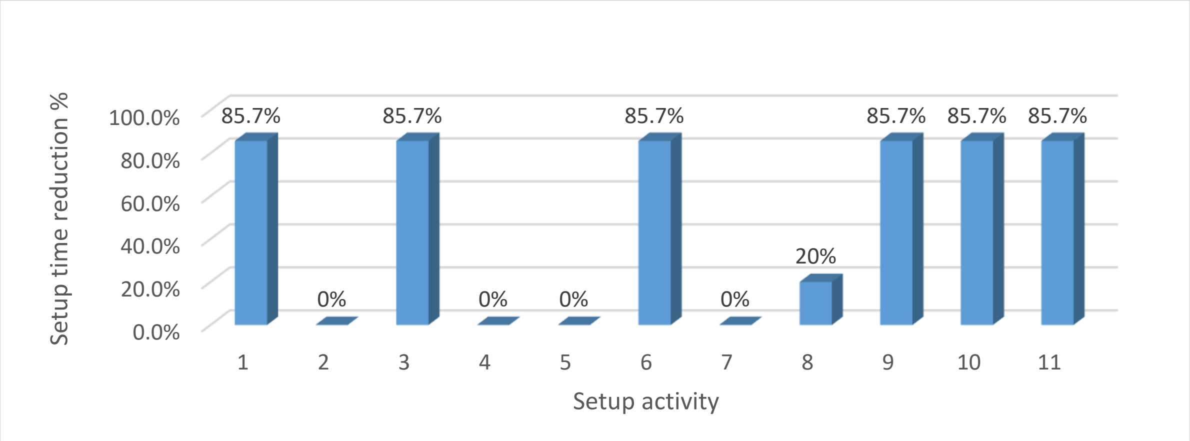


Figure 8.a: Setup activities time reduction

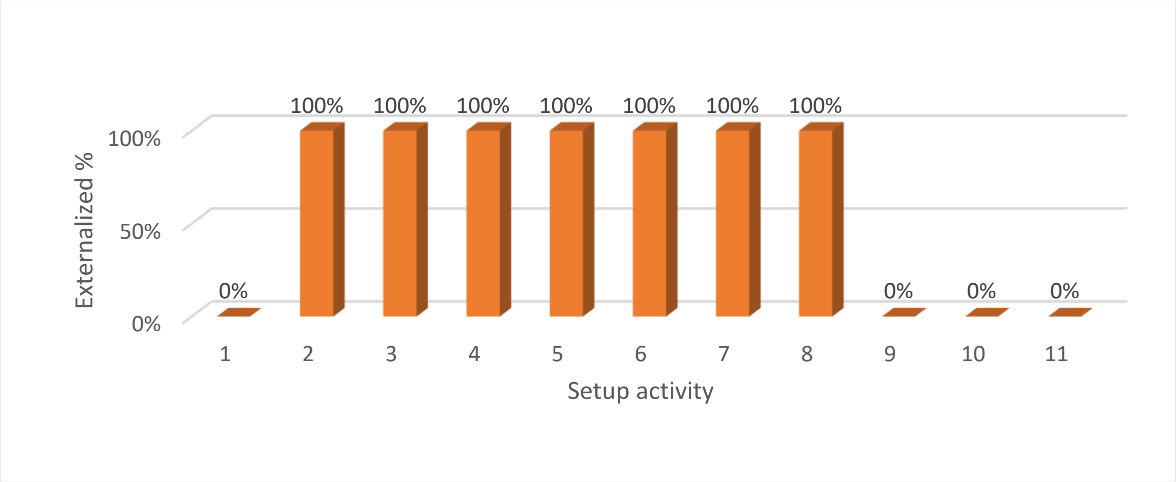


Figure 8.b: Setup activities externalization

Finally, the standardization strategy is applied to maintain the improvements. To have an overview of the results of implementing 3SM in setup processes in this paper, **Error! Reference source not found.** represents a visual comparison between before and after applying this approach. As it is shown, the combination of SMED strategies has reduced the total setup time (IST+EST) from 979 minutes to 661 minutes, where, 643 minutes of this (661 minutes) has become externalized and only 18 minutes has remained as internal setup time.

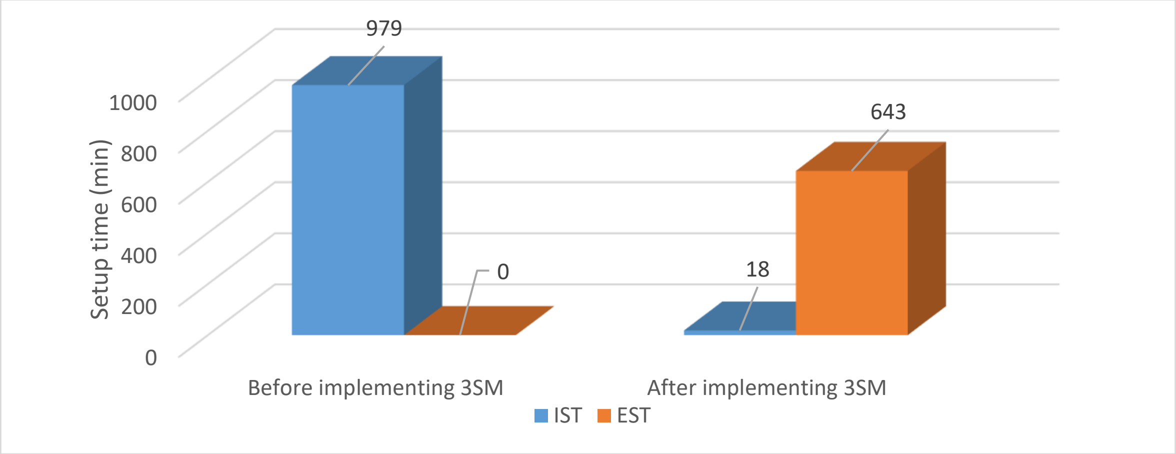


Figure 9: Overview on results of implementing 3SM in reducing setup time

In the environmental pillar of sustainability, applying 3SM leads to 20% reduction in electrical energy consumption in heating die set (Figure 10), and eliminating inventory waste in handling, because of 506 pieces reduction in inventory of cabinet foaming process (as a result of setup time reduction) that provides enough space and accuracy in inventory handling to next production process.

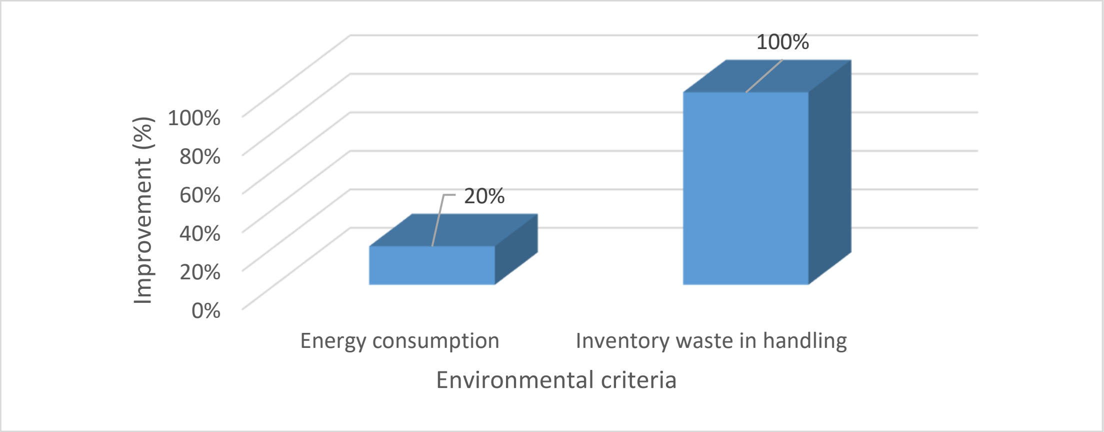


Figure 10: Overview on environmental improvement through implementing 3SM

In the social pillar of sustainability, operators waste in the cabinet foaming station and its upstream and downstream stations during the setup process, decreases 99% (**Error! Reference source not found.**), as the measured data in Figures 5 and 7 show that it has been reduced from 1780.54 mh to 15.6 mh. Also, through performing a training course to do setup tasks according to parallel execution strategy and standard instruction, skilled operators and teamwork increased 7 times as it is shown in **Error! Reference source not found.**.

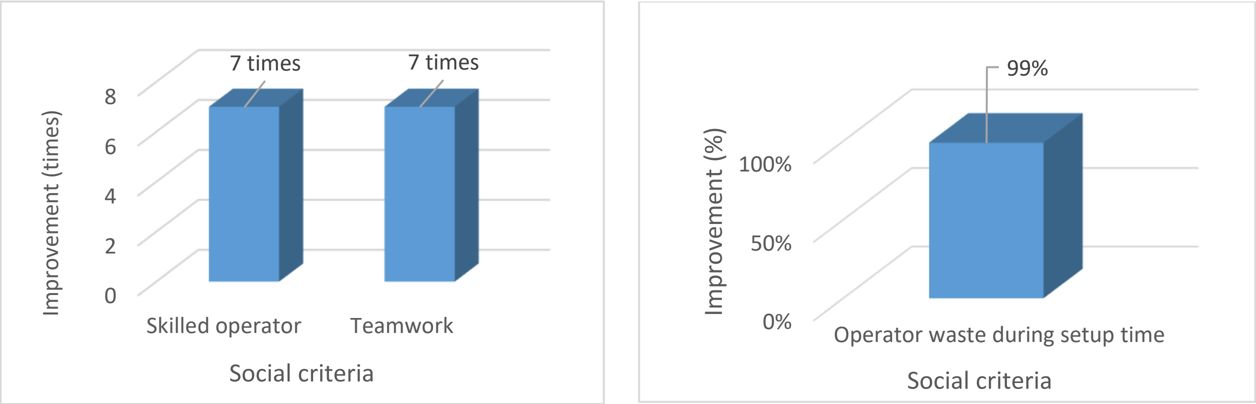


Figure 11: Overview on social improvement through implementing 3SM

In the economic pillar of sustainability, as it is presented in **Error! Reference source not found.**, through measuring the identified economic criteria in this study, significant improvements are achieved in reducing the cost of operator for internal setup operations, cost of energy consumption, inventory to keep production run during setup time, cost of inventory waste and cost of operator waste during setup time which have led to the $4254 cost reduction in each setup process. Due to annual setup times in this case study (60 times per year), $255240 cost has been reduced through implementing 3SM.

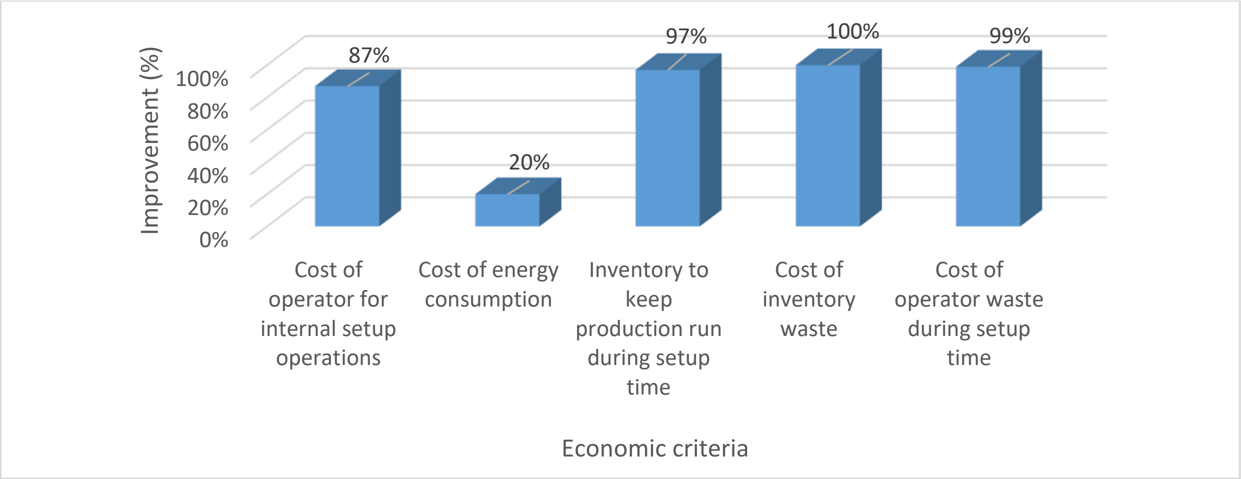


Figure 12: Overview on economic improvement through implementing 3SM

5. Conclusions

Drawing upon an extensive literature review and in-depth explorative research in discrete manufacturing industries, this study has developed a thorough practical stepwise method, named sustainable setup stream mapping (3SM), to include sustainability criteria in machine setup improvements. 3SM first employs value stream mapping (VSM) as a competent tool to analyze setup operations internally at activity and task levels, and also externally across other relevant manufacturing processes of a factory. It then employs SMED strategies (e.g. duplication, parallel execution, and standardization) to improve setup times. VSM application at the setup's activity and task levels help further improvement opportunities, which are hidden in a typical SMED, to be detected too. More importantly, 3SM recommends a list of sustainability criteria to assess the setup impacts against them, before and after setup improvements. Factory-wide mapping of the manufacturing processes, done by VSM, helps 3SM to assess the sustainability impacts of the setup operations on other relevant manufacturing processes, and make the necessary adjustments if needed.

Moreover, this paper suggests and tries a novel idea and adjustment in VSM to use it in 3SM. In the conventional VSM approach, time is divided into value-added and non-value-added parts, where lean practices are tried to eliminate non-value added time and optimize value-added time. In 3SM, although the whole setup time is non-value added, it is divided into internal setup time (IST) and external setup time (EST) to identify improvement strategies for converting IST to EST and streamlining both of them. Moreover, this paper extends the earlier developments of VSM to sustainable VSM (Faulkner and Badurdeen 2014; Helleno, Moraes, and Simon 2017) to specifically assess TBL in setup operations and their relevant processes.

The recommended 3SM method is implemented in a real-life manufacturing case study in this paper too. The results prove the practicality of the method. They show details of setup activities/tasks and sustainability criteria measurements in terms of environmental, social, and economic criteria. The case study reports considerable improvements in terms of setup time as well as the sustainability criteria. The empirical insights, drawn from the real-life case study of this research, also indicate the complexities in reaching an adequate setup time improvement and sustainability criteria across the factory.

Given the lack of well-established methods to embed and analyze sustainability criteria in the setup improvements at both setup-specific and factory-wide levels, this research goes beyond a simple application or variation of SMED and debates what specific sustainability criteria should be included and how they should be measured in setup improvements. The proposed 3SM method enhances the existing general ideas around sustainable manufacturing to a more specific level, where setup activities and tasks are focused on. Consistent with it, this paper contributes to the lean manufacturing literature by expanding the scope of SMED, as a lean tool, to sustainability improvement beyond the setup activities boundaries. The extended view of 3SM to setup and sustainability criteria, as well as its visual-analytical approach help practitioners to improve their operations in a more holistic way. Those, who have already been trained and trying lean techniques such as SMED can also implement them in a wider context of sustainability improvement of 3SM.

The variations in manufacturing processes specifically in setup operations and their effects on sustainability could be considered and studied in future studies. Setup time uncertainties can be also considered in future versions and applications of 3SM to achieve more accurate results.

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