A PDCA-based approach to Environmental Value Stream Mapping (E-VSM)

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Abstract

Research into the application of Value Stream Mapping (VSM) as a tool to enhance the environmental sustainability performance of operations has been confined to a handful of studies only. Research on this green lean research stream is therefore limited, especially when compared to the vast amount of scholarly research focused on the 'traditional' VSM tool. To complement and support the narrow body of knowledge on the application of VSM as tools to improve environmental performance and enhance the effectiveness of its application, this paper proposes an approach, based on the Deming's Plan-Do-Check-Act (PDCA) improvement cycle, to systematically implement and conduct Environmental-VSM (E-VSM) studies. The implementation of the proposed method is reported through an action research-based case study conducted in a helical rolling process of one of the mining consumables business units of an international diversified mining and materials multinational company. The results of the case study indicate that the proposed PDCA-based approach to E-VSM can be an effective alternative to improve the green performance of operations. Besides the proposal of this approach, its testing, and expanding the body of knowledge in the green lean field, the paper also contributes by providing a guiding reference for operations managers who may want to make the operations of their organisations more sustainable and environmentally friendly. Finally, this paper also intends to contribute by inspiring researchers and practitioners to broaden the study of the under-researched field which explores the application of VSM for environmental sustainability enhancement.

Keywords: Environmental Value Stream Mapping; Green Lean; Green wastes; Value Stream Mapping, VSM.

1. Introduction

Since its development by Toyota in the 1940-50s, lean has emerged as one of the most dominant managerial paradigms (Forrester et al., 2010) in business environments as extensive theoretical and empirical evidence has demonstrated its effectiveness to enhance the competitiveness of organisations (Hines et al., 2004). To achieve this, lean focuses on the fierce reduction of non-value added activities, i.e. waste, and relies on an extensive set of tools and techniques. Among the plethora of tools that lean incorporates, Value Stream Mapping (VSM) is considered one of the most essential (Belekoukias et al., 2014), with Womack (2006) considering it "the most important tool lean thinkers will need to make sustainable progress in the war against muda". VSM is a simple and visual process-based tool which enables the documentation, visualisation and comprehension of material and information flows in processes, in order to identify wastes and assist in their elimination (Nash and Poling, 2011). Over the last years, the application of VSM has not only increased within manufacturing plants and supply chains (Forno et al., 2014) but also in process industries and the service sector (Jeyaraj et al., 2013).

Underpinned by the use of VSM, and other tools and techniques, lean has contributed to the attainment of historical and contemporary organisational objectives that include profitability, efficiency, customer satisfaction, quality and responsiveness (Garza-Reyes, 2015a). However, in order to respond to and address organisations' sustainability challenges, the contribution of lean to enhance environmental performance and its integration with green initiatives have recently emerged as a contemporary research stream (Garza-Reyes, 2015a). In this context, the academic literature indicates that the relationship between lean and green has been studied in relation to (1) their synergies and divergences (Garza-Reyes, 2015b), (2) the potential benefits of their integration in different contexts (Franchetti et al., 2009), (3) their impact on organisational performance, and (4) their theoretical integration (Cherrafi et al., 2017).

To enable the synergies and integration of lean and green, a number of frameworks have been proposed and some of the lean tools adapted to assist improvements in environmental performance. For example, Cherrafi et al. (2017a) developed a framework that methodically guides companies to integrate and implement green, lean and six sigma to improve their sustainability performance. Tomelero et al. (2017) proposed a lean environmental benchmarking method for performing a diagnosis of practices and performances to support the implementation of a cutting tool management strategy. Pampanelli et al. (2014) presented an integrated lean and green approach that resulted in the reduction of production waste and environmental impact.

On the other hand, in terms of the adaptation of lean tools to support environmental objectives, due to its increasing popularity, effectiveness and relative simplicity, it is unsurprising to see that some authors have considered VSM to support the improvement of environmental and sustainability performance. For instance, Wills (2009) extended the concept of value stream, looking at it from the environmental perspective and calling it *green value stream,* also known as Environmental Value Stream Mapping (E-VSM). Torres and Gati (2009) developed an E-VSM methodology by expanding the U.S. Environmental Protection Agency's (EPA) lean and environmental toolkit. The methodology was validated through a case study conducted in the Brazilian sugar and alcohol manufacturing industry. Taking VSM as a basis, Lai et al. (2008) proposed a framework for combining life-cycle environmental input analysis, total cost analysis, and an energy consumption analysis. Kurdve et al. (2011) used an adaptation of VSM, which they also called E-VSM, at Volvo Penta Vara and Volvo Construction Equipment Braås. Folinas et al. (2014) offered a systematic approach for measuring the environmental performance of a supply chain in the agrifood sector based on VSM. Brown et al. (2014) examined in detail three case studies to demonstrate the breadth of applicability of the Sustainability-VSM tool and the aptness and limitations of the tool in assessing and visualizing sustainability performance in different manufacturing system configurations. Faulkner and Badurdeen (2014) presented a comprehensive methodology to develop Sustainable Value Stream Mapping by identifying suitable metrics and methods to visually present them. Garza-Reyes et al. (2016a) developed a sustainable version of VSM, called Sustainable Transportation Values Stream Mapping (STVSM), to improve the transport operations of a world leader logistics organisation in the metropolitan area of Monterrey, Mexico. Dadashzadeh and Wharton (2012) applied Green Value Stream Mapping (GVSM) with the aim of greening the information technology functional area of organisations. Fearne and Norton (2009) used Sustainable Value Stream Mapping (SVSM) in the food industry.

Finally, Paju et al. (2010) introduced and illustrated the application of a VSM-based assessment, named as Sustainable Manufacturing Mapping (SMM), which considers selected sustainability indicators and is based on VSM, discrete-event simulation and life cycle assessment.

The aforementioned studies have successfully demonstrated that the adaptation of lean tools, and particularly VSM, can contribute in helping organisations to address the sustainability challenges that they are currently facing due to the growth in customers' demands for more environmentally friendly products/services and compliance with governmental environmental regulations. However, despite this significant opportunity, research on this subject has been confined to the previously reviewed handful of studies only. Therefore, research on this green lean research stream may still be considered limited, especially when compared to the vast amount of studies focused on the traditional VSM found in the academic literature. To complement and support the narrow body of knowledge on the application of VSM as a tool to enhance environmental sustainability, this paper contributes to the green lean field by proposing an approach, based on the Deming's PDCA (Plan-Do-Check-Act) (Deming, 2000) method, to systematically conduct an E-VSM study. The implementation of the proposed method is also reported through an action research-based case study conducted in a grinding media manufacturer that aimed at improving the environmental sustainability of its production process, and in this way enhance its overall competitiveness. This paper also contributes by providing a guiding reference for operations managers who may wish to undertake similar improvement projects as well as by expanding the rather limited body of knowledge on environmental VSM. Additionally, this paper also intends to contribute by inspiring researchers and practitioners to broaden the study of this under-researched field. Considering this, the main research questions addressed in this study are:

- Can VSM be employed to identify and reduce the negative environmental impact of industrial operations?
- How can the traditional VSM tool be adapted and its approach systematically followed to not only document, visualise and comprehend the flows of 'traditional' material and information in processes but also consider their environmental dimension?

The rest of the paper is organised as follows: Section 2 presents the proposed PDCA-based approach to E-VSM and justifies the action research methodology followed in this study; Section 3 elucidates, through the industrial application of the proposed approach, the steps involved in its implementation. This allowed the systematic conduction of an E-VSM study which identified and eliminated/minimised green wastes that were present in the value stream of a manufacturing process in a case organisation. Finally, Section 4, presents the conclusions, limitations and future research directions derived from this paper.

2. Proposed PDCA-based approach to E-VSM and research methodology

An E-VSM, like the traditional VSM, should be considered a continuous improvement process where, based on the establishment of a current-state map and after achieving the proposed future-state map, subsequent future-state maps can be drawn to enable a continuous improvement cycle. As suggested by Rother and Shook (2003), VSM involves constant implementation plans for continuous improvement at value-stream level. Thus, and in order to continuously eliminate/minimise waste, Chiarini (2013) and Qassim et al. (2015) aligned the VSM approach with the PDCA cycle.

Based on this rationale, the PDCA-based approach to E-VSM implementation presented in Figure 1 was proposed to provide an effective method to enable the deployment of E-VSM studies in a systematic, repeatable, and continuous cycle of improvement manner. The approach was developed based on three 'design stages'. The first stage entailed studying the features, reason for adapting, and applicability of VSM to improve environmental/sustainable performance. This ensured the amalgamation of the most relevant and current theoretical knowledge into the proposed framework (Garza-Reyes et al., 2016b). The second stage consisted in using the theoretical and industrial experience of the authors as consultants, practitioners, academics and researchers to assist the development of the proposed approach. According to Rocha-Lona et al. (2013), these play an important role when creating theoretical frameworks which will be deployed in industry. Lastly, the third stage included the consideration of relevant input from the case company where the approach was applied. Therefore, similarly to the work of Garza-Reyes et al. (2016b), discussions with relevant executives, directors, managers and shop-floor staff and initial observations of the company's value stream were also conducted to consider key parameters and issues relevant to E-VSM studies.

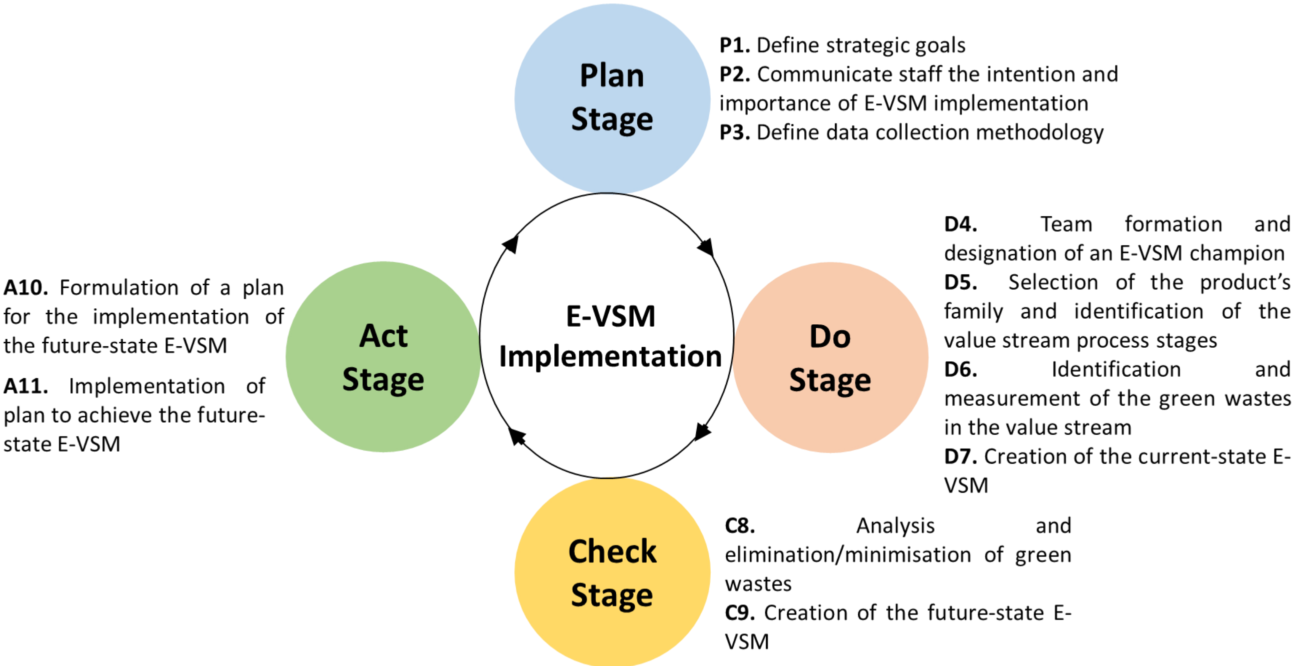

Figure 1. PDCA approach to E-VSM implementation

Once developed, the PDCA approach to E-VSM implementation was applied in one of the mining consumables business units of an international diversified mining and materials multinational company. Specifically, the application focused on a helical rolling process that manufactures grinding ball products, see Figure 2. This manufacturing process was selected due to the strategic importance it represented for the case organisation. The practical application of the proposed approach led to an empirical study which most appropriate research methods are action research or case study (Shadish et al., 2002). Since this work required the presence and participation of the researchers to manage, lead, aid and closely track the implementation and management of the proposed PDCA-based approach to E-VSM, action research was considered the most suitable method for this study. This method also helped, through the direct intervention of one of the researchers, in overcoming problems and resistance during the application of the proposed approach (Gutierrez et al. 2015). In this study, and as advocated by Coughlan and Coghlan (2002), action research evidenced to be an effective method not only to document and report the experiences and lessons learnt by the authors while carrying out the E-VSM but also to test it and draw conclusions regarding its effectiveness. For this reason, action research was found to be a valuable research strategy that contributed in advancing the body of knowledge of the green lean field.

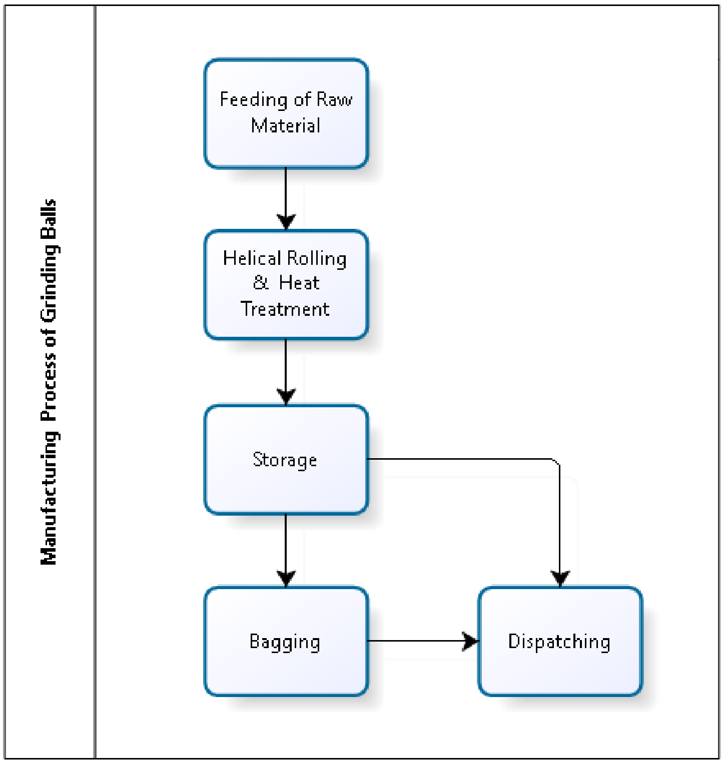

Figure 2. Grinding balls manufacturing process overview

3. PDCA-based approach to E-VSM definition and application

3.1 Plan stage

P1. Define Strategic Goals

Clear objectives provide a pathway for organisations to become lean (Chiarini, 2013). Therefore, at the Plan stage, the formulation of goals is important to give the E-VSM implementation a focal point. In this sense, the strategic goal for its application in the case organisation was to effectively identify and measure environmental wastes in the value stream of the helical rolling process, see Figure 2, to then formulate and undertake suitable strategies to eliminate/minimise it in order to move on to the future-state.

P2. Communicate to staff the intention and importance of E-VSM implementation

Following, within the Plan stage it is also important to communicate the staff the goals for implementing the E-VSM. Employees' commitment to the project is essential since their participation and feedback will provide a linkage towards continuous improvement and the creation and achievement of the current and future-state maps (Abdulmalek and Rajgopal, 2007). Additionally, environmental practices will only be successfully implemented if these are accompanied by the enhancement of employees' knowledge and competence regarding environmental issues (Cherrafi et al., 2017). In this case, the intention and importance of E-VSM implementation was carried out through a communication campaign that included departmental meetings, staff briefings and training on sustainability and E-VSM.

P3. Define data collection methodology

In a VSM study, a rigorous and systematic data collection methodology needs to be defined in order to ferret out sources of waste and find ways to eliminate them (Qassim et al., 2015). The same applies to the implementation of E-VSM. For this project, the data collection strategy consisted in formulating and following a pre-established data collection plan that included the gathering of green data regarding different characteristics of the value stream of the studied process. In particular, the data collected included characteristics such as (1) energy and water consumptions; (2) usage rate of the devices/equipment that operated at each process stage of the value stream – this in order to identify the greatest consumers and reduce their usage; (3) water toxicity level and its grade of impurity – this in order to understand the sort of toxins handled in the process and adopting the most suitable cleaning alternative; (4) the grade of recyclability and biodegradability of the materials and substances employed in the process – this in order to understand how much may be able to be reused and how harmful material could be; and finally (5) the amount and sources of total emissions generated by the process. The data was gathered through direct observations and measurements of the value stream using some data collection forms created by the authors. To do this, the entire value stream of the studied helical rolling process was followed and observed from end to start (Rother and Shook, 2003) for a period of one month.

3.2 Do stage

D4. Team formation and designation of an E-VSM champion

The next step in the proposed PDCA-based approach to E-VSM consists of forming the team that will carry out the E-VSM implementation and the designation of the champion who will ensure that adequate support is provided to the team and that any barriers that may arise during the E-VSM implementation are removed (Garza-Reyes et al., 2016b). The E-VSM team was formulated with employees who were directly involved in and responsible for various stages of the value stream of the studied process. Furterer (2009) and Garza-Reyes et al. (2016b) suggest that in improvement projects, team members should be selected from those who have adequate knowledge and background on the process. Therefore, the team included the Production Manager responsible for the process, two Team Leaders and one of the authors. The Production Manager was responsible for the full operation of the process, whereas the team leaders supported its operation. The participant author was the leader of the E-VSM implementation. In addition, the Plant Manager championed the E-VSM project. As suggested by Rother and Shook (2003) and Wills (2009), the champion had the authority to make change happen, along with providing leadership to the process, also had complete knowledge of lean and green practices, and an understanding of the product's family and operational processes.

D5. Selection of the product's family and identification of the value stream process stages

The case organisation manufactures three different families of grinding media products, namely: grinding balls, grinding rods, and mining chemicals for mineral treatment. Each product's family manufacturing process is completely different from the other in terms of equipment and processes employed. As commented by Womack (2006) and Rother and Shook (2003), it is necessary to select a product family before starting a VSM study. Thus, after having formed the team and designated the champion, the next step in the proposed PDCA-based approach to E-VSM is to select the product's family.

For this study, the grinding ball product was selected. Grinding balls are manufactured from steel bars in different sizes and for different applications, e.g. ball mills or SAG mills. Grinding balls are employed in mineral processing ball milling operations, varying in size from 1.0 inch to 4.0 inches in diameter. They are manufactured from high carbon-alloy steel bars. Each diameter of ball has its own chemical composition and heat treatment. SAG balls are designed for SAG mill mineral processing operations. Sizes are within a range from 4 inches to 6.25 inches in diameter. In the same manner, each diameter of SAG balls is manufactured with a particular chemical composition from alloy and its corresponding heat treatment.

As suggested by Saboo et al. (2014), the selection of the grinding ball product's family was decided based on the following strategic factors:

a) It was the biggest product family in terms of turnover for the case organisation. This meant that when focusing this study on the main source of materials consumption, energy use, and assets utilisation; a great portion of waste, contamination, and pollution generators would be addressed;

b) Customer had indicated increasing volumes over the following years;

c) The manufacturing process of this specific product involved the use of all major equipment; hence it increased the scope and impact of the E-VSM improvement project.

The value stream of the grinding balls manufacturing process is illustrated in Figure 2. This was identified as indicated in P3.

D6. Identification and measurement of the green wastes in the value stream

In the proposed approach, the procedure to build the current E-VSM starts with identifying and measuring seven environmental, or green, wastes adapted from the works of Wills (2009), Torres and Gati (2009), Brown et al. (2014) and Faulkner and Badurdeen (2014), i.e. (1) energy, (2) water, (3) materials, (4) garbage, (5) transportation, (6) emissions, and (7) biodiversity. *Energy waste* appears when consuming more energy than required. This, in turn, generates a more negative environmental impact when the source of energy are fossil fuels. *Water waste* emerges when using more water than needed and subsequently having to pay for getting it cleaned. *Materials waste* is appointed to materials used to build a product which, after having accomplished the product life cycle, cannot be reused and end up in the landfill. *Garbage waste* is when the garbage generated cannot be reused, it generates a negative environmental impact, and companies have to pay to dispose it. *Transportation waste* comes from unnecessary journeys in the value stream process, which in turn generate a more negative environmental impact when the transportation means burning fossil fuels. *Emissions waste* is referred to creating and discharging contaminants into the atmosphere. The last green waste is *biodiversity*, which is related to the destruction of flora, fauna, and organisms; and also consuming natural resources in excess. This waste, however, was considered out of the scope of this project as it requires historical data from the case company regarding the type and amount of biodiversity that existed before the establishment of its facilities/operations, for which data did not exist.

In this case, green wastes were identified and measured sequentially at each process stage of the value stream, see Figure 2. This step prior to the construction of the current-state map was undertaken along with the data collection activity, see Section 3.1, P3. All the information and data gathered was noted in waste elimination forms prepared for this purpose. The systematic method followed to identify and measure the six green wastes in the value stream of the helical rolling process is shown in Figure 3. Some examples of the data collected and captured in the waste elimination forms are exemplified in Figure 4.

Identification and Measurement of Energy Waste

I. Identification of machinery, equipment, or installation whose operation involves the consumption of energy in the form of either electricity or fuel.
II. Gathering of the values of energy either electricity or fuel consumed in each of the identified operations.
III. Measurement of the usage rate for each operation identified.
IV. Calculation of the total energy consumption for each operation during a period of time. This is a simple multiplication of the energies values consumed per the usage rate.
V. Calculation of the cost of using the energy. For this, it is necessary to know the price of energy fixed by the provider.

Identification and Measurement of Water Waste

I. Identification of any equipment or activity in the value stream whose operation consumes water.
II. Determine the flow rate of water per equipment.
III. Determine the usage rate during a period of time.
IV. Calculation of the total consumption of water during a period of time. This is a simple multiplication of the quantity of water consumed per the usage rate.
V. If the system employed retains water, then the difference between the quantity of water consumed and the quantity of water retained would be the water discharged. Otherwise, if the system does not retain water, the quantity of water discharged would be equal to the water consumed.
VI. Measure the toxicity of the water discharged.

Identification and Measurement of Materials Waste

I. Identification of the input materials in the process stage.
II. Assignation of the input material makeup with its chemical composition.
III. Identification of the output materials in the process stage.
IV. Specify whether the input material is made up of recycled or biodegradable materials. If so, note the percentage of recycled or biodegradable material.
V. Specify whether the output materials may be recycled or may be biodegradable after the end of its lifecycle. If so, note the percentage of recyclability or biodegradability.
VI. Classification of the output materials either technical nutrient (recyclable), biological nutrient (biodegradable), or landfill (waste).
VII. Assessment of the environmental and human health impact that represents the output materials.

Identification and Measurement of Garbage Waste

I. Finding out the garbage bins, cans, or bags situated in the area where each process stage takes place.
II. Identification of the composition of the garbage containers and its material makeup.
III. Measurement of the quantity or weight of garbage items dumped during a time frame.
IV. Classification of the environmental and human health impact that represents the garbage items found. Such classification is done according to the criterion shown in the following figure

Green	Little or no risk to the environment or human health.
Yellow	Low or moderate risk. It is acceptable for use at least it can be substituted with one rated
Red	High impact and risk. Phasing out and replacing it with a green or yellow rated.
Grey	Risk data unknown or incomplete. Further investigation is needed to rate the material.

Identification and Measurement of Transportation Waste

I. Identification of the activities in the value stream requiring transportation for either raw material, WIP, or finished goods.
II. Identification of the mode of transportation employed.
III. Measurement of the distances travelled.

Identification and Measurement of Emissions Waste

I. Find out the sources of emissions and effluents in the value stream.
II. Identification of the type of emissions and effluents coming from each source found out.
III. Measure the amount of emission or effluent during a time frame.

Figure 3. Systematic method to identify and measure the six green wastes (adapted from Wills, 2009)

Garbage Waste Elimination Worksheet			
Product:	**Grinding Balls 2.1/2"**		
Production Line:	**Helical Rolling 2**		
Step:	**1. Feeding of Raw Material**		
Current State			
Identify	Measure		
Item	Material	Quantity	Assess
Wire Rod Box	Wire rod	1,441.2 kg/month	Yellow

a) Process stage: Feeding of Raw Material; Green waste: Garbage

Energy Waste Elimination Worksheet									
Product:	**Grinding Balls 2.1/2"**								
Production Line:	**Helical Rolling 2**								
Step:	**2. Helical Rolling & Heat Treatment**								
Current State									
Identify		Measure							
Equipment	Source	Rate		Usage		Consumption			
						Qty		Cost (USD/kW-h)	
Electrical Motors for Bars Feeding	Electricity	2	kW	84.3	h/month	168.7	kW-h/month	8.10	
Electrical Motors for Bars Heating (x3)	Electricity	6	kW	84.3	h/month	506.0	kW-h/month	24.29	
Converters	Electricity	3100	kW	337.3	h/month	1,045,630.0	kW-h/month	50,190.24	
Electrical Motors for Converter Cooling	Electricity	20	kW	337.3	h/month	6,746.0	kW-h/month	323.81	
Electrical Motors for Water Cooling	Electricity	20	kW	337.3	h/month	6,746.0	kW-h/month	323.81	
Fan Motors Cooling Tower 1 (x2)	Electricity	150	kW	112.4	h/month	16,866.5	kW-h/month	809.59	
Electrical Motors for Hydraulic Units	Electricity	100	kW	337.3	h/month	33,730.0	kW-h/month	1,619.04	
Electrical Motors for Hydraulic Units Cooling	Electricity	30	kW	337.3	h/month	10,119.0	kW-h/month	485.71	
Fan Motors Cooling Tower 2 (x2)	Electricity	150	kW	112.4	h/month	16,865.0	kW-h/month	809.52	
Electrical Motors for Rolls Cooling	Electricity	10	kW	337.3	h/month	3,373.0	kW-h/month	161.90	
Prime Motor	Electricity	1000	kW	337.3	h/month	337,300.0	kW-h/month	16,190.40	
Electrical Motor for Prime Motor Cooling	Electricity	15	kW	337.3	h/month	5,059.5	kW-h/month	242.86	
Electrical Motor for Gearbox Cooling	Electricity	3.5	kW	337.3	h/month	1,180.6	kW-h/month	56.67	
Electrical Motor for Cooling Table	Electricity	2.2	kW	337.3	h/month	742.1	kW-h/month	35.62	
Electrical Motor for Quenching Drum	Electricity	20	kW	337.3	h/month	6,746.0	kW-h/month	323.81	
Electrical Motor for Quenching Water	Electricity	20	kW	337.3	h/month	6,746.0	kW-h/month	323.81	
Fan Motors Cooling Tower 4 (x2)	Electricity	150	kW	112.4	h/month	16,865.0	kW-h/month	809.52	
Drive	Electricity	1000	kW	337.3	h/month	337,300.0	kW-h/month	16,190.40	
Lighting (x30)	Electricity	12	kW	337.3	h/month	4,047.6	kW-h/month	194.28	
AC	Electricity	5	kW	337.3	h/month	1,686.5	kW-h/month	80.95	

b) Process stage: Helical Rolling and Heat Treatment; Green waste: Energy

Transportation Waste Elimination Worksheet			
Product:	**Grinding Balls 2.1/2"**		
Production Line:	**Helical Rolling 2**		
Step:	**3. Storage**		
Current State			
Identify	Measure		
Item	Mode	Unit Distance	Total Distance
Grinding Balls Boxes 6t	Bridge Crane	100 m / trip	46,983 m

c) Process stage: Storage; Green waste: Transportation

Materials Waste Elimination Worksheet								
Product:	**Grinding Balls 2.1/2"**							
Production Line:	**Helical Rolling 2**							
Step:	**4. Bagging**							
Current State								
Identify	Measure							
Input		Output	Material Makeup		Classify			Assess
Item & Qty	Material Makeup	Item	Input	Output	Technical Nutrient (Recyclable)	Biological Nutrient (Biodegradable)	Landfill	
Polypropylene Bag (422 units/month)	100% Polypropylene	Polypropylene Bag	0% recycled	100% recyclable	X			Yellow

d) Process stage: Bagging; Green waste: Materials

Emissions Waste Elimination Worksheet		
Product:	**Grinding Balls 2.1/2"**	
Production Line:	**Helical Rolling 2**	
Step:	**5. Dispatching**	
Current State		
Identify	**Measure**	
Item	**Type**	**Amount**
Forklift 3t	NOx	14.6 gr/month
Forklift 3t	CO_2	51.3 gr/month

e) Process stage: Dispatch; Green waste: Emissions

Figure 4. Evidence of data collected from the six green wastes in some process stages

D7. Creation of current-state E-VSM

After the identification and measurement of the green wastes, the following step in the proposed approach to E-VSM is to create the current-state map. For this purpose, the methodology suggested by Rother and Shook (2003) to construct a traditional VSM was adapted to incorporate the six green wastes previously discussed. Thus, a blueprint of the value stream, depicting each process step in data boxes, see Figure 5, with its corresponding values of green wastes previously measured was developed. The blue print also illustrated how the raw material was received and how the finished product was delivered by using a track symbol, as well as the direction of the information flow that supported the helical rolling process. A broken arrow was used to indicate the flow of electronic information and a solid arrow for physical flows. The E-VSM sequence was the same as that shown in Figure 2. The current E-VSM is shown in Figure 6.

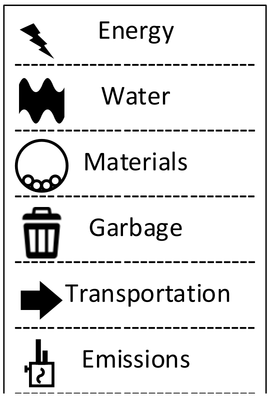

Figure 5. Data boxes used to depict green wastes

3.3 Check stage

C8. Analysis and elimination/minimisation of green wastes

Similarly as the current-state map of the traditional VSM, the current-state E-VSM map enables the evaluation of process operations, but in this case, in relation to green rather than non-value added/lean wastes (Dickson et al., 2009). Clear identification of waste, either in the form of materials, information flows, or even green wastes, in the current-state map is essential to identify performance improvement opportunities in the future-state map (Hamad et al., 2012). This will support the improvement team on the task of formulating and implementing effective strategies for their elimination/reduction. Thus, after creating the current E-VSM, the following step in the proposed approach refers to the analysis, interpretation and proposal of strategies for the elimination/minimisation of the identified green wastes.

For this study, the analysis process to eliminate/minimise the green wastes identified in the current-state E-VSM was constituted by a number of strategies proposed by Wills (2009), along with the selection of appropriate lean tools and techniques that supported such elimination/minimisation. Table 1 presents the green waste elimination strategies formulated for every stage of the helical rolling process, whereas Table 2 indicates the specific activities that were considered as part of the strategies followed. Additionally, Figure 7 presents an example of the analyses carried out in order to assess the effectiveness and potential impact of the strategies to address the green wastes. These analyses served as the basis to create the future-state E-VSM, see step C9 in the following section.

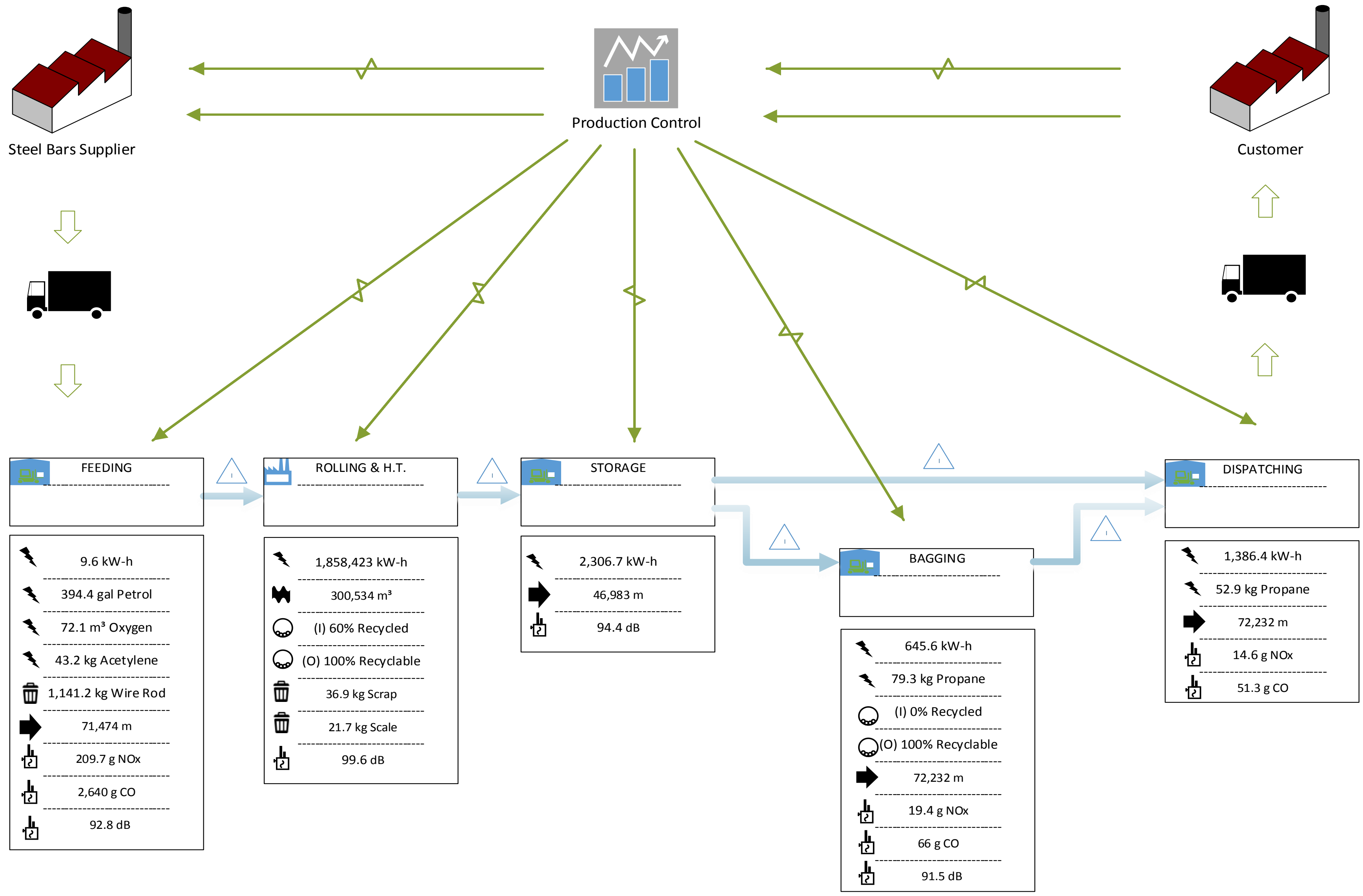

Figure 6. Current-state E-VSM for the helical rolling process to manufacture grinding balls

Table 1. Strategies for the elimination of green wastes in every stage of the helical rolling process

Wastes \ Process Stages	Feeding of Raw Material	Helical Rolling and Heat Treatment	Storage	Bagging	Dispatch
Energy	• Conservation • Adoption of efficient technologies • Energy management • Alternative sources				
Water		• Conservation • Toxicity minimisation • Reuse			
Materials		• Pursuing 100% reuse • Using recycled input and output materials • Minimising usage • Elimination of negative impact materials		• Pursuing 100% reuse • Using recycled input and output materials • Minimising usage • Elimination of negative impact materials	
Garbage	• Minimisation • Reuse	• Minimisation • Reuse			
Transportation	• Minimisation of distances • Alternative eco-friendly transportation		• Minimisation of distances • Alternative eco-friendly transportation	• Minimisation of distances • Alternative eco-friendly transportation	• Minimisation of distances • Alternative eco-friendly transportation
Emission	• Minimisation at the source	• Minimisation at the source		• Minimisation of emissions at the source	• Minimisation at the source

Negligible or no waste of that type in that stage of the process

Table 2. Activities considered as part of the green wastes elimination/minimisation strategies

Waste	Strategy	Actions/Alternatives
Energy	Energy conservation	• Developing procedures to disconnect devices when not required to work • Utilising timers, sensor, etc. to automatically shut off devices when not in use • Regulating devices operations according to the intensity of specific tasks
	Adoption of efficient technologies	• Acquire devices/equipment with minor energy consumption
	Energy management	• Using energy for a period of the day when total charge of devices is low. Barriers may involve changing working schedules • Moving energy usage to off-peak times
	Alternative sources	• Adopting energy generators such as geothermal, biomass, windmills, solar panels, and hydro turbines
Water	Water conservation	• Implementing operational procedures, either automatic or manual, to shut-off machine/water valves when not required; putting in place maintenance programmes to fix leaking dispensers; investigating whether water is supplied in the quantity needed and when required • Using water-efficient technologies
	Toxicity minimisation	• Tackling first water system that discharges the highest content of toxins and the one with the highest impact in reducing fines • Concentrating on eliminating most harmful toxins from the source • If eliminating the source of the toxins is unviable, cleaning the toxicity of the water is an option
	Reuse	• Classify discharged water according to its grade of impurity ▪ Clean Water – suitable for drinking ▪ Grey Water – not suitable for drinking but may be used again ▪ Black Water – must be treated • Decide where to employ clean or grey water
Materials	Pursuing 100% reuse	• Design processes that allow a product to get back at the end of its life
	Using recycled input and output materials	• Use input materials that have higher recycled contend • Producing goods highly recyclables
	Minimising usage	• Implementing effective practice, e.g. lean, to minimise excessive use of materials
	Elimination of negative impact materials	• Eliminate materials categorised with high impact and risk on environment/human health, i.e. those categorised as red in environmental impact assessments
Garbage	Minimisation	• Identify origin of garbage by identifying the process/activity where garbage is generated • Analyse whether amount of garbage can be reduced/eliminated by changes in the process/activity that generates it • Analyse which materials can be recycled or biodegraded • Indicate quantity of garbage that may be diverted from going to landfill.
	Reuse	• Changing size, shape, or characteristics of employed materials to make them recyclable, reusable, or biodegradable

Transportation 	Minimisation of distances	• Implementing cellular manufacturing practices
	Alternative eco-friendly transportation	• Implementing, using or adapting eco-friendly fuels and transportation ways
Emission 	Minimisation at the source	• Identify source of emission and note it in waste elimination worksheet • Investigate whether process is working under design parameters • Investigate whether process/activity can use less emissions since excess of material means excess in cost and emissions • Investigate whether source of emission can be replaced by a more eco-friendly substitute • Examine options for altering, changing, or eliminating the emission provoking activity

C9. Creating of the future-state E-VSM

The current-state map provides a snapshot of the actual process operations and performance in an ‘as-is’ form (Saboo et al., 2014). This helps in identifying wastes and hence prioritise and direct improvement efforts and resources more efficiently (Braglia et al., 2006). However, the actual effectiveness of a VSM study lies not only on this characteristic but also on its capability to provide a vision and develop a value stream that depicts the ideal state of a process (Brown et al., 2014). In this context, the future-state map enables businesses to look into the future by defining an ideal approach and performance to operate a process’ value stream. In other words, a future VSM depicts the ‘as-it-should-be’ state (Barbereto Henrique et al., 2016). In the case of an E-VSM study, the future-state map should portray the improvements that a process’ value stream can attain by incorporating the green wastes elimination/minimisation strategies formulated in the previous step of the PDCA-based approach to E-VSM.

Figure 8 presents the future-state map, i.e. ideal future-state, of the helical rolling process by showing the potential improvements that it may achieve after the implementation of the green wastes elimination/minimisation strategies formulated and assessed in the previous stage. The process of creating the future E-VSM was the same as that followed during the creation of the current-state map. In this case, the potential reduction of green wastes indicated by the analyses, see Figure 7, were transcribed to and illustrated in the future-state map. These are shown in the future-state map by noting the potential reduction that may be achieved in the header box of each process stage. Moreover, the adjusted values after subtracting the amount of potential waste reduction from the current values are noted in the data boxes to reflect the future-state that is pretended. This is an important step in an E-VSM study as the future-state map shows the environmental improvements that may be achieved by eliminating or reducing the green wastes identified in the current-state map.

Garbage Waste Elimination Worksheet						
Product:	Grinding Balls 2.1/2"					
Production Line:	Helical Rolling 2					
Step:	1. Feeding of Raw Material					
Future State						
Minimise					Reuse	
Material	Source of Garbage	Change	Recycle / Biodegrade	Savings	Solution	Savings
Wire rod	Bundle of raw material		Already 100% recyclable		Send it back to the steel bar suppliers	1,441.2 kg

a) Process stage: Feeding of Raw Material; Green waste: Garbage

Transportation Waste Elimination Worksheet				
Product:	Grinding Balls 2.1/2"			
Production Line:	Helical Rolling 2			
Step:	3. Storage			
Future State				
Minimise			Eco-Transortation	
Item	Distance Solution	Savings	Solution	Savings
Grinding Balls Boxes 6t				

c) Process stage: Storage; Green waste: Transportation

Materials Waste Elimination Worksheet								
Product:	Grinding Balls 2.1/2"							
Production Line:	Helical Rolling 2							
Step:	4. Bagging							
Future State								
Minimise								
Item & Qty	Harmful Materials		Proposal for Minimise	Savings	100% Technical & Biological Nutrient	100% Technical & Biological Nutrient Outputs	Reuse	Savings
Polypropylene Bag	Rated yellow	Do not requires change			0%	Already 100%		

d) Process stage: Bagging; Green waste: Materials

Energy Waste Elimination Worksheet									
Product:	Grinding Balls 2.1/2"								
Production Line:	Helical Rolling 2								
Step:	2. Helical Rolling & Heat Treatment								
Future State									
Minimisation									
Equipment & Devices	Energy Conservation		Energy-Efficient Technologies		Energy Management		Alternative Source of Energy		
	Solution	Savings	Solution	Savings	Solution	Savings	Solution	Cost	Savings
Electrical Motors for Bars Feeding	Study of setup processes Development of procedures Classification of delay's root-cause Ishikawa and 5W Lean techniques for roots-cause analysis	USD 39,633.12 per year Reduction of Scrap			Already applying Energy Management				
Electrical Motors for Bars Heating (x3)									
Converters									
Electrical Motors for Converter Cooling									
Electrical Motors for Water Cooling									
Fan Motors Cooling Tower 1 (x2)									
Electrical Motors for Hydraulic Units									
Electrical Motors for Hydraulic Units									
Fan Motors Cooling Tower 2 (x2)									
Electrical Motors for Rolls Cooling									
Prime Motor									
Electrical Motor for Prime Motor									
Electrical Motor for Gearbox Cooling									
Electrical Motor for Cooling Table									
Electrical Motor for Quenching Drum									
Electrical Motor for Quenching Water									
Fan Motors Cooling Tower 4 (x2)									
Drive									
Lighting (x30)	Procedures to disconnect devices when not required its service and at the required intensity		Already use Energy-Efficient Technologies						
AC									

b) Process stage: Helical Rolling and Heat Treatment; Green waste: Energy

Figure 7. Evidence of strategies' assessment for green wastes in some process stages

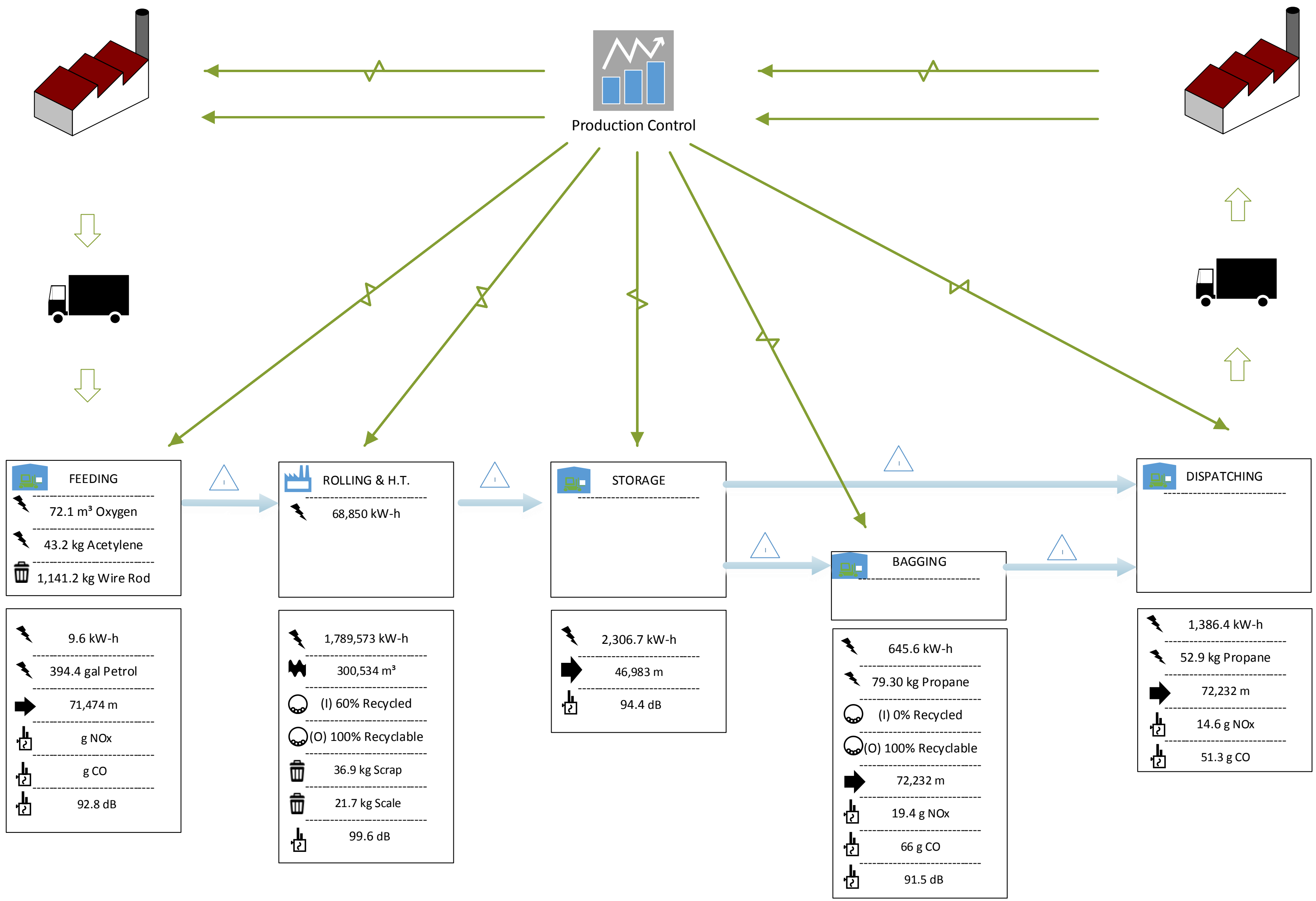

Figure 8. Future-state E-VSM for the helical rolling process to manufacture grinding balls

3.4 Act stage

A10. Formulation of a plan for the implementation of the future-state E-VSM

Once that the future-state map has been created, the following step in the proposed method consists in the origination of a plan to implement the strategies conceived to eliminate/minimise the green wastes, and in this way ‘transform’ the studied value stream into its desired future-state. In this context, the establishment of objectives and goals form the basis of a plan as these provide the rationale to go forward and a clear direction as to what needs to be done and achieved (Chiarini, 2013). Objectives and goals will also serve as a basis for monitoring and controlling the progress and success of the E-VSM implementation. This aspect is an essential element in the deployment of lean practices as Kumar and Phrommathed (2006) comment that the absence of monitoring and controlling activities on the implementation of lean results in failures towards a lean transformation. Thus, to develop an implementation plan, individual objectives and goals were set to address the green wastes. Additionally, as suggested by Wilson (2010), key performance indicators (KPIs) were also established for each individual objective and goal, with the premise that they should be easy to understand and compare with benchmarks or standards. This was essential as KPIs enable the measurement and tracking of the implementation progress of an E-VSM future-state map. An objective and goal-based plan, also including KPIs, was formulated for every stage of the helical rolling process. Table 3 shows an example of a future-state E-VSM implementation plan formulated, particularly, for the helical rolling and heat treatment stage of the helical rolling process.

Table 3. Objective and goal-based implementation plan for future-state E-VSM - helical rolling and heat treatment stage

Process Stage	Objective	Measurable Goal	KPI
Helical Rolling and Heat Treatment	Measure all set-up delays	Every cause of delay categorised and measured	Delay time [hrs]
	Stabilisation of set up times	5.9 hrs	Set up time [hrs]
	Reduction of energy consumption	3.7%	Energy consumption KW-h/month
	Reduction of water consumption at cooling towers	5.0%	Water consumption [m^3/month]
	To have specific spots to measure volume discharged and toxicity for each water system	4 water systems	Water discharged [m^3/month] ; Toxicity rate [gr/m^3]
	100% of water use discharged from converters cooling system	100%	Volume of reused water [m^3]
	Measure all scrap	Every cause of scrap generation categorised and measured	Scrap volume [kg/month]
	Reduction of scrap generation	50%	Total Scrap volume [kg/month]
	Quantify amount of garbage, i.e. grease, hydraulic oil and oil rags quantified	100% of disposed grease, hydraulic oil and oil rags quantified	Grease [kg/month]; Oil volume [m^3/month]
	Reduce the use of grease	25%	Grease volume [kg/month]

	Reuse hydraulic oil	100%	Hydraulic Oil Volume [m^3/month]
	Eliminate oil leaking	none	Number of leaking spots

A.11 Implementation of plan to achieve the future-state E-VSM

The implementation of the plan formulated in the previous stage is the last step in the proposed approach to E-VSM. Thus, this step corresponds to the execution phase that will deliver and enable the 'transformation' from the current to the future-state E-VSM. In practice, constraints in resources such as investment, time, personnel, etc. may make the implementation of all the strategies devised to eliminate the green wastes impossible to deploy at the same time. This is because, according to Marriot et al. (2013), organisations can only assign limited resources to the improvement of their processes, services and/or products. For this reason, it might be necessary to prioritise the implementation of those strategies based on those that will provide optimum solutions with high benefits and relatively low implementation costs (Garza-Reyes et al. 2016b). Techniques that may aid in the prioritisation of the strategies may include Pareto priority index and Analytical Hierarchy Process (AHP) (Pyzdek, 2003) as well as scoring techniques against essential criteria such as process impact, risk impact, business impact, cost impact, etc. (Garza-Reyes et al. 2016b), among others.

Once that some specific strategies have been prioritised, an action plan must be created by the team, or person, designated to be in charge of implementing the green wastes elimination/minimisation strategies. The action plan may include the assignment of resources to certain implementation activities and an implementation evaluation. The implementation evaluation is a process for reassessing the empirical implementation of the proposed strategies (Mostafa et al., 2013). The evaluation can be done by regularly comparing the objectives and goals achieved against the progress made at specific points in time during the implementation timeframe.

According to Rother and Shook (2003), the best way to start with the implementation of a future-state VSM is from the peacemaker process (Qassim et al., 2015). This is the closest process to the customer (Saboo et al., 2014), which acts as an internal customer, then going upstream through the other processes of the value stream. Under this condition, the peacemaker process for this study was considered to be the dispatching stage, see Figure 2. For this reason, the implementation of the plan to achieve the future-state E-VSM was initiated in this stage of the helical rolling process, and later moved upstream through bagging, helical rolling & heat treatment, to complete it in the feeding of raw materials process stage. Figure 9 shows an example of a future-state E-VSM implementation plan. A suggested by Rother and Shook (2003), the implementation plan is presented in the form of a Gantt chart.

The full implementation of the plan and hence of the prioritised green wastes elimination/minimisation strategies is currently under way in the case organisation; thus, it is still not possible to present the final results of this E-VSM study and determine its success. However, extensive empirical evidence, such as that provided by Prashar (2017) and Zhang et al. (2015), suggests that a systematic approach with logically and well-defined sequenced transitional stages, such as those facilitated by the proposed PDCA-based approach to E-VSM, will provide a more effective and efficient approach to operations improvement (Garza-Reyes et al., 2016b). Therefore, it is possible to predict that if the implementation plan is successfully deployed, the case organisation will be able to reduce some of the environmental wastes as suggested by the comparison between the current and future-state E-VSMs.

Future-State Environmental Values Stream Implementation Plan

Product Family: Grinding Balls 2.5"

E-VSM Champion: Joseth Torres

Process Stage	Objective	Goal Measurable	KPI	Monthly Schedule												Person in Charge	Implementation Team	Review Schedule	
				1	2	3	4	5	6	7	8	9	10	11	12			Reviewer	Date
Bagging / Dispatching	Having a thorough control of fuel consumption of forklift powered by liquid petroleum gas	Meet design specifications of the equipment	Fuel Consumption [kg/km]																
Helical Rolling & Heat Treatment	To have all kind of setup delays measured	Every cause of setup delay categorised and measured	Delay Time [hours]																
	Stabilisation of set up times	5.9 hours	Setup Time [hours]																
	Reduction of energy consumption	3.7%	Energy Consumption kW-h/month																
	To have all kind of scrap measured	Every cause of scrap generation categorised and measured	Scrap Volume X [kg/month]																
	Reduction of scrap generation		Total Scrap Volume [kg/month]																

Figure 9. Example of a future-state EVSM implementation plan

4. Concluding Remarks, Limitations and Future Research

This paper presents a novel PDCA-based approach to systematically conduct an E-VSM analysis. The research is therefore among the very limited number of studies, see Section 1, which have considered the application of the highly used VSM tool to address the environmental challenges currently faced by organisations. For this reason, this study advances our knowledge in the field of green lean and fills a research gap, as previously highlighted in Section 1, by:

- Providing further evidence of the application of lean methods and tools, specifically VSM, and validating their effectiveness to address the critical environmental issues created by unsustainable manufacturing operations;
- Proposing a logically and well-defined sequenced approach, based on the Deming's PDCA method, for companies to systematically conduct E-VSM studies;
- Presenting the application of the proposed approach not only to validate it but also to serve as a guiding reference for operations managers who may wish to undertake similar improvement projects; and (hopefully)
- Inspiring researchers and practitioners to conduct further studies on green lean, and specifically, the application of VSM as a tool to enhance environmental sustainability in order to broaden the study of this under-researched field.

These contributions are beneficial for manufacturing managers, and their companies, who aim to improve the green performance of their operations by using lean principles, tools and techniques. Due to the extensive applicability of VSM, and lean, in other sectors where they have also been deployed, e.g. healthcare, services, logistics and transport, etc., these are also likely to benefit from the approach proposed in this paper. These industrial sectors are under increasing pressure to be more environmentally sustainable and the effective implementation of E-VSM can provide them with an opportunity to achieve this endeavour.

Within the context of the case organisation, the results obtained from the implementation of the proposed PDCA-based approach to E-VSM suggest that it can be an effective alternative to improve the green performance of operations. This corroborates the positive results also obtained by studies discussed in Section 1 when using VSM to enhance environmental and sustainability performance.

In this particular case, it is suggested that if the case company effectively implements the action plan to deploy the green waste elimination/minimisation strategies, it will be able to reduce the consumption of energy and the production of garbage in the feeding and helical rolling and heat treatment stages of its manufacturing process that produces grinding balls. This provides an important practical contribution for organisations that can use the proposed PDCA-based approach as a reference to conduct similar improvement projects. We hope that our proposed approach would also encourage industrialists, and thus their companies, and assist them in achieving more environmentally sustainable operations. To advance this area further, research is needed to provide an understanding of the benefits, challenges and define the critical success factors for the effective deployment of E-VSM studies, similarly as indicated by Andreadis et al. (2017) in reference to traditional VSM studies. On the other hand, the PDCA-based approach to E-VSM proposed in this paper was specifically applied within the context of the manufacturing operations of only one organisation. Therefore, further research can focus on validating this approach in other companies not only to improve manufacturing operations but also other type of operations such as logistics and transport, healthcare, services, among others. Finally, the E-VSM tool itself can be developed further to be able to concurrently identify, quantify and eliminate/reduce both green and 'traditional' operational wastes, e.g.

inventory, set-up delays, breakdowns, etc. This would allow an E-VSM study to determine the impact that reducing green wastes may have on other measures of operational performance such as lead-time and cost/efficiency. These research streams are some of the main future research directions proposed from this work.

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