Assessing the impact of fusion-based additive manufacturing technologies on green supply chain management performance

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Abstract

Purpose – This paper aims to identify the impacts of wire and arc additive manufacturing (WAAM) technology on the green supply chain management (GSCM) performance. Also, it intends to identify the most essential WAAM capabilities.

Design/methodology/approach – An exploratory case study related to a metallurgical company using WAAM technology to repair metallic components was developed. A research framework to identify WAAM production capabilities and the different GSCM performance criteria was proposed based on the current state of the art. Primary qualitative data provided evidence for developing seven propositions relating WAAM capabilities to GSCM performance.

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Findings – The paper provides empirical evidence relating to how WAAM production capabilities impact the different performance criteria of the GSCM performance. The results show that “relative advantage” and “supply-side benefits” are critical capabilities developed through WAAM. Furthermore, most of the capabilities regarding “relative advantage” and “supply-side benefits” promote a higher GSCM performance.

Research limitations/implications – This research was carried out using a single case study research design and using qualitative data. Thus, future works are encouraged to test the propositions empirically using quantitative methodologies.

Practical implications – The case study findings support that most WAAM production capabilities promote a higher GSCM performance. Managers could use this research to understand the capabilities developed by this fusion-based additive manufacturing (AM), become aware of the implications of new technology adoption on the supply chain environmental externalities, and develop new business models based on the WAAM capabilities.

Originality/value – This research contributes to expanding the state-of-the art related to WAAM technology by evidencing the relationship between adopting this fusion-based AM technology and green supply chain practices. Also, it provides a set of seven propositions that could be used to theorise the impacts of WAAM adoption on the GSCM performance.

Keywords Wire arc additive manufacturing, Fusion-based additive manufacturing, Additive manufacturing, Green supply chain management, Supply chain, Performance

Paper type Research paper

1. Introduction

The relationship between the environment, governmental globalisation policies and industrial development have forced manufacturing companies to shift towards incorporating sustainable practices (Sahoo and Vijayvargy, 2020). Factors like the sustainable supply of natural resources, environmental and political constraints in the supply chain, cost pressures related to sustainability and environmental externalities are gaining importance for sustainable economic models of business (Kazancoglu *et al.*, 2018; Vijayvargy *et al.*, 2017). Adopting new technologies such as additive manufacturing (AM) brings new challenges in terms of business sustainability, requiring a broad view of manufacturing systems, spanning the company’s internal process and the whole supply chain (Ford and Despeisse, 2016).

The use of technology and technical knowledge is a source of innovation for the development of new and improved products and services. This means that companies need to develop their production capability, investment capability and innovation capability to make the most of technology (Dahlman *et al.*, 1987). The so-called manufacturing or production capabilities represent a company’s ability to efficiently combine several resources to engage in productive activities and produce products that satisfy the market’s needs (Ferdows and De Meyer, 1990). Recent studies have identified possible impacts of adopting AM technology (Arifin *et al.*, 2022; Bappy *et al.*, 2022; Kuzmenko *et al.*, 2022); however, there is a lack of explorative studies that measure effectively the adoption of these technologies in different contexts and as a factor of the companies’ competitive advantage (Niaki and Nonino, 2017).

AM is an emerging technology highly suitable for producing parts in small batches and with a high level of customisation (Niaki and Nonino, 2017; Yuan *et al.*, 2022). Wire and arc additive manufacturing (WAAM) is a fusion-based AM technology known for its high deposition rate, low material waste and cost-effective manufacturing processes and for being suitable for the repair and/or fabrication of medium to large metallic components (Yuan *et al.*, 2022). The research surrounding this topic is still in its infant stage in terms of state-of-the-art implications concerning parametrisation, deposition strategies, new materials and part quality (Dias *et al.*, 2022). Adopting WAAM technology represents an opportunity for companies to develop new production capabilities. However, there are no studies giving indications of what those capabilities would be.

Despite the advantages surrounding AM, the existing literature is mainly concerned with its environmental and economic aspects (e.g. Rinaldi *et al.* (2021), Niaki and Nonino (2017) or Costabile *et al.* (2017)) and respective life cycle models (Kokare *et al.*, 2022); there are few studies addressing this technology social impacts (Naghshineh *et al.*, 2021). AM contributes to improving supply chain efficiency as a result of waste reduction, less energy consumption and elimination or reduction of pre-assembly and assembly activities, thus contributing to "greener" production processes (Torres *et al.*, 2020). Currently, organisations worldwide are trying to reduce and minimise their environmental impact by integrating environmental concerns into supply chain management operations and practices – called green supply chain management (GSCM) (Tseng *et al.*, 2019). Even though in a nascent stage, there are already some studies exploring the impact of adopting AM technology on GSCM, as shown by Torres *et al.* (2020) and Rinaldi *et al.* (2021). However, there are no studies exploring the relationships between WAAM and GSCM. Thus, this research intends to address this research gap by assessing the impacts of WAAM technology on GSCM performance. For that, two research questions (RQ) are to be answered in an exploratory research design:

RQ1. What are the most important WAAM production capabilities?

RQ2. How do WAAM production capabilities impact the GSCM performance?

To address these research questions, an explorative case study was carried out (Yin, 2009), following the same research methodology as Naghshineh and Carvalho (2022). Here, we assessed the implementation of WAAM by a metallurgical start-up whose focus is on repairing parts. Seven propositions were developed using the case study evidence to infer the most relevant WAAM production capabilities, and they impact the GSCM performance.

The paper is structured as follows: Section 2 contains the literature review concerning the main topics under study and presents the conceptual framework developed to carry out this research. Section 3 presents the research methodology, followed by Section 4, which contains the results. Finally, section 5 includes the main conclusions.

2. State-of-the-art and research framework

2.1 Green supply chain performance

The supply chain plays an important role in operations management and significantly impacts the environment, including pollution, community health hazards and emissions, amongst others (Tseng *et al.*, 2019). Improvements in companies' economic and/or environmental performance require organisational actions (such as environmental management systems or cleaner production) that should be considered and implemented throughout the supply chain (Azevedo *et al.*, 2011; Yildiz Çankaya and Sezen, 2018). To Tseng *et al.* (2019), integrating environmental concerns into supply chain management practices is designated as GSCM. Srivastava (2007) defines GSCM as "*integrating environmental thinking into supply-chain management, including product design, material sourcing and selection, manufacturing processes, delivery of the final product to the consumers as well as end-of-life management of the product after its useful life*". The GSCM helps companies accomplish a more significant market share and corporate profit by reducing environmental risks while improving ecological efficiency (Drohomeretski *et al.*, 2014).

The GSCM involves several initiatives and practices. Dubey *et al.* (2017) distinguished between soft and hard dimensions, with the former being related to human resources, while the latter relates to technology, strategy and policy adopted by organisations to implement GSCM successfully. The "soft dimensions" include, for example, customer relationship or supplier relationship practices, which enable sustainable environmental solutions of their services or products in line with their customer needs (Kazancoglu *et al.*, 2018) or criteria for choosing a specific material or service supplier. The "hard dimensions" include practices such as green manufacturing or eco-design. Green manufacturing involves converting inputs into the required outputs, with the minimum production of hazardous substances that might be harmful to the environment and human health, without risking the product quality (Dubey *et al.*, 2017; Yildiz Çankaya and Sezen, 2018). Eco-design relates to product development while minimising the environmental impact of a product's life cycle. It includes design for remanufacturing (to facilitate reworking activities), repairing and refurbishment to return the product to ideal conditions for continuous operation

(Dubey *et al.*, 2017). Another important practice in GSCM is the reverse logistics, which focuses on the return of products and materials from the point of consumption to the supply chain system, to reuse, recycle, repair, remanufacture, refurbish the products and materials, or to provide for their safe disposal (Eltayeb *et al.*, 2011). Another GSCM practice is the green purchasing, which focuses on cooperation with suppliers to develop environmentally sustainable products (Green *et al.*, 2012).

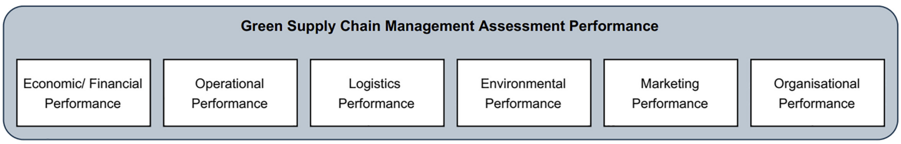
In the literature, a large set of empirical data has been supporting the direct link between adopting GSCM and improved performance (Bhatia and Gangwani, 2021; Dubey *et al.*, 2017). Overall, GSCM aims to reduce resource consumption and costs and decrease environmental pollution by improving market share, ensuring green production and a stronger brand image, and thus, increasing an organisation's economic performance (Kazancoglu *et al.*, 2018). GSCM practices may enhance environmental performance by reducing environmental pollutant levels (Kazancoglu *et al.*, 2018) or through waste minimisation (Tseng *et al.*, 2019). Moreover, the successful implementation of GSCM can be termed as a strategy to improve organisational performance and sustainability (Dubey *et al.*, 2017).

Measurement of organisational performance encompasses qualitative and quantitative methods. However, the level and variety of the selected performance measures vary with the company's goal or the business's specific characteristics (Hervani *et al.*, 2005). This study adopted the performance assessment framework developed by Kazancoglu *et al.* (2018). This framework is built on a three-level hierarchy that starts at the top level by six main criteria (as showed in Figure 1): economic/financial performance (related to the minimisation of environmental activities that concern to material procurement, consumption of energy, treatment and discharge of waste, profit increase, cost reduction and market share growth), operational performance (defined as the capability of an organisation in satisfying its customers in terms of delivery quality products and efficiency in production, while decreasing inventory and scrap levels), logistics performance (defined by green logistics as an environmentally-friendly efficient transportation), environmental performance (evaluated according to factors such as compliance level with regulations, products, services and processes of the company towards environment and consumption of resources), marketing performance (evaluates the relationships between corporate performance and marketing activities and practices) and organisational performance (a measure to evaluate an organisation's success level to accomplish its objectives). Kazancoglu *et al.* (2018) split these six main criteria into 21 sub-criteria, which are translated by 189 measures.

Many studies have explored the integration of GSCM with other supply chain paradigms, such as lean manufacturing (Azevedo and Carvalho, 2019). Lean and green manufacturing aims to achieve low levels of waste (including operational and environmental themes) and better overall efficiency (Carvalho *et al.*, 2017). This can be achieved by finding new ways to create economic, social and environmental value (Zailani *et al.*, 2015). The GSCM strategy of a company is intimately connected to its technological innovation. A better understanding of GSCM performance could help companies innovate more and adopt innovative technologies (Lee *et al.*, 2014; Rinaldi *et al.*, 2021).

2.2 Wire and arc additive manufacturing–WAAM

Companies are adopting different innovations and digital technologies (Alcácer and Cruz-Machado, 2019). Amongst them, AM brings new challenges to supply chains (Büyüközkan and



Source(s): Adapted from Kazancoglu *et al.* (2018)

Figure 1.
GSCM performance assessment criteria

Göçer, 2018). AM technology is expected to transform production processes due to its ability to transform a computer model into a 3D structure via a layer-by-layer deposition process (Cruz Sanchez *et al.*, 2020). AM technology provides state-of-the-art solutions for multiple manufacturing sectors and can increase a company's competitiveness. AM is defined as "*the process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies, such as traditional machining*" (Oettmeier and Hofmann, 2017). According to Colorado *et al.* (2020), seven main process categories are included in AM: (1) material jetting, (2) material extrusion, (3) vat photopolymerisation, (4) binder jetting, (5) directed energy deposition and (6) powder bed fusion.

This innovative technology allows the production of complex shapes from different materials, such as polymers, metals and composites (Singh *et al.*, 2017) and has become increasingly popular for product customisation, manufacturing parts with complex geometries, prototyping and small batches production (Faludi *et al.*, 2019). Using AM technology makes it possible to create and develop complex shapes while reducing the waste produced and the time spent developing the product (Shanmugam *et al.*, 2020). AM can replace classical subtractive production technologies while increasing process efficiency (Barz *et al.*, 2016) and can be used locally at the point of consumption, and thus, instantaneously addressing the community's needs through the designing and manufacturing of tailor-made services and products that are delivered faster, as a result of a shorter and simpler supply chain (Kravchenko *et al.*, 2020; Rylands *et al.*, 2016). Furthermore, AM contributes to a reduction in complexity and stock level by replacing assembly steps in production and facilitating component consolidation (Mohr and Khan, 2015), thus decreasing supply chain complexity. According to Luomaranta and Martinsuo (2022), AM adoption is not limited to a single company and spans value chains. Spare parts can be produced on-site, transforming suppliers' roles within production lines (Cruz Sanchez *et al.*, 2020).

Potential environmental benefits arise from adopting AM technology, for example, Kellens *et al.* (2017) concluded in their review that the appropriate selection of AM processes and technologies can lead to significant savings in resource and energy consumption. AM is expected to contribute to a reduction in environmental load when compared to traditional manufacturing, especially regarding the energy consumption and materials used, due to the decrease in the amount of waste generated during the AM processes (Colorado *et al.*, 2020). Kravchenko *et al.* (2020) point out that AM could be suitable for original equipment manufacturing, maintenance, repair and remanufacturing activities, avoiding the production of new components and supporting strategies that focus on materials for implementing circular economy systems, thus, positively contributing to the production of recycled materials and local recycling (Kellens *et al.*, 2017). Moreover, it has been argued that AM can be cost-effective, leading to the creation of new business opportunities, which can benefit from competitive advantage through retaining customers by engaging them in the co-creation of customised services and products (Kravchenko *et al.*, 2020), resulting in high customer satisfaction levels (Faludi *et al.*, 2017).

Although these benefits are important for all AM processes, research on the use of WAAM is steadily increasing with contributions from both industry and academia due to the advantages of this process (Rodrigues *et al.*, 2019b). WAAM is a fusion-based AM technique where a solid wire is fed into an electric arc, melt, and is subsequently deposited onto a substrate (Ding *et al.*, 2015). This AM technique allows the quick manufacturing of large metallic parts with a lower equipment cost and a higher deposition rate (Lopes *et al.*, 2020). WAAM parts tend to have highly structural integrity; thus, it is only necessary to perform machine-finishing operations (Lopes *et al.*, 2020). WAAM consumes less material waste than selective laser melting and does not expose operators to such hazardous manufacturing conditions. It is, therefore, a more environmentally friendly process (Oliveira *et al.*, 2019). WAAM is less costly, has a higher deposition rate and is safer than other metal-based techniques such as electron beam melting and selective laser melting (Rodrigues *et al.*, 2019a).

Consequently, WAAM is a key enabling technology for fabricating large metallic parts, including in high-value industries such as aerospace (Ding *et al.*, 2014). In addition, WAAM can be used for repair operations, unlike powder-bed technologies (Abe *et al.*, 2019; Ríos *et al.*, 2018, 2019), although the use of WAAM technology for repair operations is in its infancy (Pagone *et al.*, 2022). In fact, with this technology, in-loco repairs can be performed instead of completely replacing a part, reducing costs associated with repair operations (Rodrigues *et al.*, 2019a). Arifin and Frmanzah (2015) suggested that the adoption of new technologies such as WAAM can be linked to improvements in a company's performance, such as: lower operational costs, improved effectiveness (better accountability and flexibility) and efficiency (through cost reduction) and less environmental impact. These improvements are related to developing new production capabilities or attributes derived from the technology implementation and its integration into the company activities and processes. These production capabilities are associated with the routine operations but also with factors such as skills, equipment, organisational systems and management methods (Chiesa and Manzini, 1996; Christensen, 1995). Therefore, it is expected that AM helps to develop the companies' production capabilities. Oettmeier and Hofmann (2017) propose four bundles of AM innovation attributes: (1) technology-related factors ("relative advantage" and "ease of use"); (2) firm-related factors ("absorptive capacity" and "compatibility"); (3) market structure-related factors ("external pressure" and "perceived outside support"); and (4) supply chain-related factors ("supply-side benefits" and "demand-side benefits"). These are production capabilities that are expected to be developed by the adoption of AM.

Following the work of Oettmeier and Hofmann (2017), we consider in this research that a company only adopt WAAM technology if there is an expectation to enable a set of production capabilities. Therefore, "relative advantage", "supply-side benefits", and "demand-side benefits" are considered as the WAAM production capabilities. Table 1 summarises the capabilities of a production system that can be developed through WAAM.

Many studies have been performed over recent years to capture and understand the impact of AM processes and technologies, mainly focusing on environmental performance (Garcia *et al.*, 2018). WAAM, for example, as still in its infancy, has been actively explored by academics and practitioners but is mainly related to economic performance, environmental performance and some social performance dimensions (Bekker and Verlinden, 2018; Bours *et al.*, 2017; Dias *et al.*, 2022). Although AM, and thus, WAAM, can improve performance levels, there is currently a research gap between its adoption and its subsequent impact on the GSCM performance (Torres *et al.*, 2020).

WAAM production capabilities	Items*
Relative advantage (RA)	Cost reduction Improved material usage Ability to build lightweight products Freedom of design Ability to optimise products for function and integrate more functionality into an object
Supply-side benefits (SSB)	Reduction and simplification of manufacturing steps Elimination of pre-assembly activities Facilitated separation between product design and manufacturing tasks Reduced need for transportation services Reduction of the supplier base
Demand-side benefits (DSB)	Production closer to the customer Faster reaction to changing customer needs Customised production Higher customer service level

Note(s): *Measurement items retrieved from Oettmeier and Hofmann (2017)

Table 1.
WAAM production capabilities

2.3 Research framework

We aim to explore the relationship between WAAM production capabilities and GSCM performance. To achieve this, it is necessary to identify a set of GSCM performance criteria suitable for a company that uses WAAM technology. For that purpose, the framework developed by Kazancoglu *et al.* (2018) to assess the GSCM performance was used. WAAM technology has a relatively low technology readiness level (TRL), and its adoption is still in its infancy (Rodrigues *et al.*, 2019a). Therefore, it is difficult to evaluate this technology's impact on a company's environmental and organisational performance. This research considered the following GSCM criteria: economic/financial performance, operational performance, logistics performance and marketing performance. However, not all sub-criteria proposed by Kazancoglu *et al.* (2018) can be used to assess the GSCM performance of a company that adopts WAAM. For example, in the economic/financial performance dimension, it is not possible to fully assess the revenue attained by adopting this technology because companies are still testing different business models to generate the most value from WAAM. Similarly, in the operational performance dimension, the green packaging does not apply to the products produced by WAAM technology since they are usually produced in-loco. Table 2 resumes the criteria and sub-criteria considered in this research to assess the GSCM performance of a company that uses WAAM technology.

To assess the impact of WAAM capabilities on the GSCM performance, we developed a conceptual framework that links the different WAAM production capabilities to the GSCM performance (see Figure 2).

GSCM performance criteria	GSCM performance sub-criteria*
Economic/financial performance	Cost oriented
Operational performance	Increase in quality
	Increasing efficiency
	Improving green manufacturing
	Improving Eco-Design
Logistics performance	Improving green logistics
	Improving reverse logistics
	Improving green purchasing
Marketing performance	Increasing customer satisfaction
	Improving cooperation/collaboration with customers

Note(s): *Sub-criteria retrieved from Kazancoglu *et al.* (2018)

Table 2. Main criteria to assess the GSCM performance of a company adopting the WAAM technology

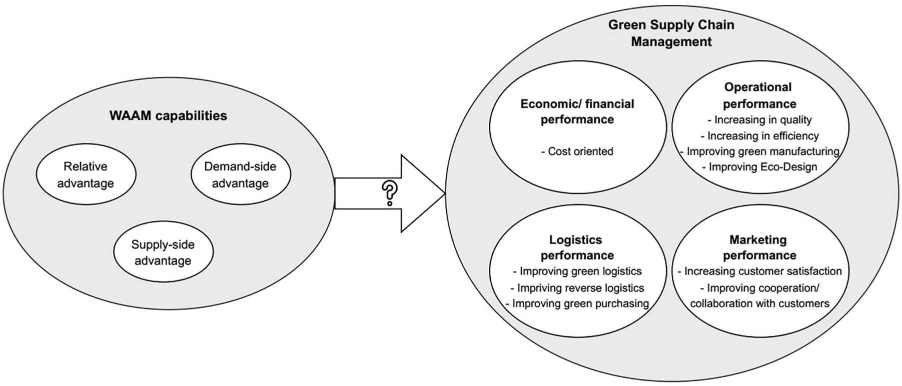


Figure 2. Framework to assess the impact of WAAM production capabilities in the GSCM performance

3. Methodology

Yin (2009) emphasised that case studies can be descriptive, explanatory or exploratory. Since there is still little empirical evidence of how WAAM technology impacts the GSCM performance, it is too early to develop testable hypotheses; thus, this research is exploratory. The case study method was considered to be the most appropriate to achieve the research objectives, given the lack of evidence in the existing literature about the phenomena under study. We aim to contribute to the current knowledge body by proposing a set of propositions to assess the impact of WAAM production capabilities on the GSCM performance. The research uses the qualitative data-analysis scheme proposed by Miles *et al.* (1994), which involves the development of a conceptual framework with simultaneous data gathering and display, followed by the proposal of propositions. Other authors, such as Azevedo *et al.* (2011), Oettmeier and Hofmann (2016) and Niaki and Nonino (2017), have used a similar methodology in the domains of GSCM performance and AM.

3.1 Study design, case selection and sampling

This research aims to understand the WAAM production capabilities and their expected impact on GSCM performance. Considering the phenomenon under study is still in its early stages of investigation, a single case study is suitable to obtain in-depth knowledge about the phenomenon under study and to identify issues that had not been explored before (Voss *et al.*, 2002; Yin, 2009). This research design may be viewed as a significant contribution to theory building and knowledge (Yin, 2009). A similar approach was made with success by Naghshineh and Carvalho (2022) to study supply chain vulnerabilities and AM adoption; they used a single case as a pilot case to serve as a base for future multiple case studies. Thus, we chose an exploratory research design in this research, focusing on a single company that already had adopted WAAM technology.

Since our focus is on WAAM technology, the first decision criterion for the case study selection was that the company under study must use this technology in its daily operations. A search was done on LinkedIn to find out how many companies used this fusion-based additive technology. Using the keywords "additive manufacturing WAAM", a total of 15 organisations (comprising companies and research institutes) were found. As Rosenzweig and Singh (1991) recommended, because the supply chain's environmental behaviour is country-dependent, it is necessary to concentrate on a single case in one country before moving on to a more comprehensive evaluation of multiple supply chains across different countries and continents. Following this, the European geography was used as a second decision criterion for the case study selection. A population of six European organisations were found. After analysing the companies' profiles and public information (e.g. the website), it was found that only two companies explicitly use WAAM technology to repair, refurbish and produce large metal parts. One of the companies promptly agreed to actively participate in the study, the start-up Guaranteed, which uses WAAM technology to repair large metal equipment. It should be noted that this process for case study selection does not intend to obtain a probabilistic sample from a given population; it intends to find the most suitable case for the research purpose, as recommended by Voss *et al.* (2002) and Yin (2009).

Since this is an exploratory work, it is desirable to cover a limited number of tiers in the supply chain to discern the possible relationships proposed in the conceptual framework (Azevedo *et al.*, 2011). Therefore, a single supply chain exploratory case study was carried out, considering a dyadic relationship between the start-up Guaranteed and one of its main clients, Company A (whose name was asked to remain confidential). Company A is a European steel plant and contracts Guaranteed services to repair rollers used for steel production. Figure 3 contains a representation of the supply chain under study.

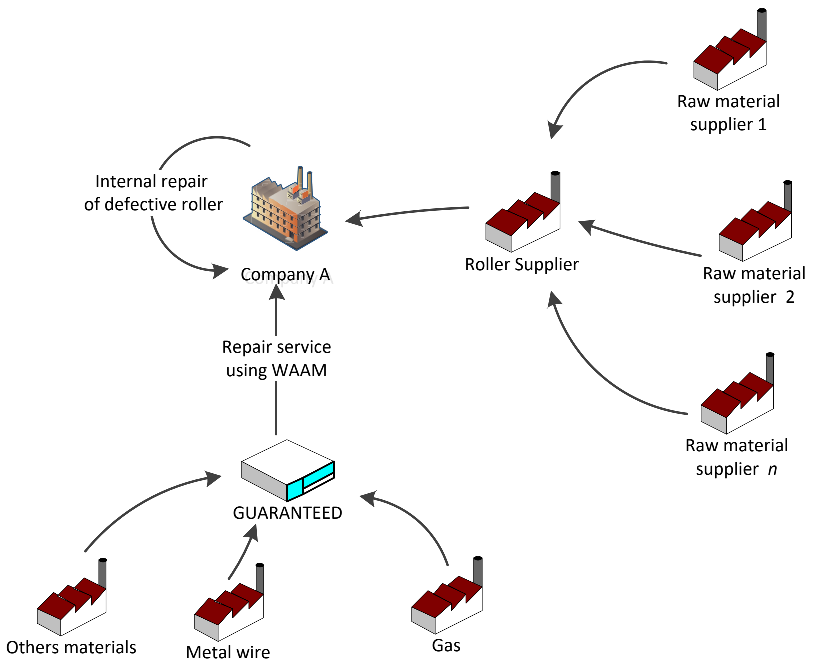


Figure 3. The supply chain of the case under study

3.2 Data collection and analysis

The primary data set was obtained by enquiring a single expert using interviews and questionnaires. The expert, the general manager of Guaranteed, has more than 20 years of professional experience in the steel manufacturing industry. In his past functions, he worked in Company A, so he has deep knowledge of Company A's internal processes and supply chain. In addition to the interviews and questionnaires, complementary queries were elaborated to obtain clarifications and validate results. A set of secondary data was obtained from the company's internal documents, reports and databases. The objective was to understand how WAAM will be implemented in the current supply chain.

An interview protocol was devised based on the theoretical background related to WAAM technology and its impact on GSCM performance. The proposed protocol was validated by one academic expert in WAAM technology development and implementation. This step is fundamental to narrow the research scope while maintaining a critical and detailed assessment of the WAAM's impact on the GSCM performance. The interview with the general manager of Guaranteed was essential to understanding how WAAM technology was implemented and how the supply chain work.

Afterwards, questionnaires A and B (available in Appendix section) were developed and sent to the expert. Before sending the questionnaires, they were validated by the research team.

Questionnaire A was used to evaluate the importance of each WAAM production capability for enhancing the company's performance. The measured items are retrieved from Oettmeier and Hofmann (2017), as shown in Table 1. Following the suggestion of several researchers, such as Zhu *et al.* (2005), Urgal-González and Manuel García-Vázquez (2007) and Ferreira *et al.* (2019), it was used a 5 points Liker-type scale, e.g. from "1 = not important" to "5 = very important" to capture the expert knowledge.

Afterwards, questionnaire B was used to assess the impact of each WAAM production capability's impact on the GSCM performance. The items used in this questionnaire were retrieved from Kazancoglu *et al.* (2018), as shown in Table 2. As Azevedo *et al.* (2012) suggested, a relationship matrix was used to assess the impact of each WAAM capability in the several GSCM performance dimensions. After receiving the expert responses, an unstructured interview was performed to capture evidence that supports the emerging relationships between WAAM production capabilities and GSCM performance.

The data collected from the case study was organised and displayed in tabular displays, which will be further presented and discussed in Section 5. To answer the first research question related to the importance of the different WAAM capabilities in a company's production system, a cross-category analysis was performed, followed by a within-category analysis. To answer the second research question concerning the impact of WAAM technology on GSCM performance, data from the questionnaires were analysed and complemented with exerts from the unstructured interview. From these, a total of seven propositions were devised to assess the impact of WAAM production capabilities on the GSCM performance. These propositions were elaborated based on the evidence collected in the case study setting and are justified with exerts from the interviews.

3.3 Case study description

Large industrial production equipment is often tailor-made, resulting in long lead times when components break down or even complete replacement of entire installations when components become obsolete, original moulds have been lost, or suppliers have gone bankrupt. This leads to either huge financial losses due to (unplanned) lengthy production standstills or high storage and logistic costs for storing slow-moving replacement parts. WAAM technology offers a solution to these problems, making it possible to repair and rebuild large, slow-moving parts on demand, reducing lead times and eliminating storage costs. Manufacturing cost reduction can be an additional advantage as no dies, tools, mould or setup costs are required. The case study is related to a new start-up company, Guaranteed, which delivers value for its customers by repairing, refurbishing and producing large metal parts using WAAM. Overall, Guaranteed uses this fusion-based AM technology to extend industrial equipment lifetime, allowing its customers to reduce spare parts stock and reduce the downtime of their industrial equipment. This is an Eco-Design practice, one of the core practices of GSCM. The company uses state-of-the-art advanced simulation tools to guarantee first-time-right production while guaranteeing one-stop-shop reliability.

One of the leading industrial sectors targeted by Guaranteed is the steel industry. As steel is a commodity product, steel plants must operate 24/7 throughout the year, as this determines the sector's profitability. The plant production equipment is often unique or tailor-made and is exposed to severe operating conditions requiring high structural integrity and a long lifetime. Being a "mature" industry, obsolescence is becoming a major concern. One of Guaranteed's customers, a European steel plant, Company A, aims to use the technology to repair rollers used for steel production. If a roller contains surface defects, ruptures or leakages, it is removed from the production line and replaced by a new one. Broken or excessively worn rollers can no longer be used and are considered scrap, which is recycled internally. In a steel production line, 4 to 10 variants of rollers may be used. These rollers are produced by a single supplier using centrifugal casting technology. Since these rollers are not off-the-shelf products, lead times can be significant. Although Company A belongs to a multinational corporation, it manages its own stock of rollers, ensuring that there are enough rollers to replace defective ones. To reduce the acquisition cost, negotiation with the supplier is handled by centralised corporate purchasing. The roller stock represents around 0.5% of the company's stock value.

Together with Guaranteed, company A is considering using welding repair through WAAM to repair defective rollers on-site and reintroduce them later in the production line. WAAM technology makes it possible to recover defective rollers, extending their lifetime and preventing catastrophic failures. The repair time for a single roll is estimated to be less than

3 h and results in expected cost savings exceeding several hundred thousand euros due to the avoidance of premature leaking and/or surface damage and the consequent reduction in the number of new rollers needed. There is an expectation that inventory levels and logistics costs will be reduced. Prolonging the life of ageing industrial equipment will reduce disposal and recycling costs since 20 tonnes of metal are not sent to scrap, and material waste is reduced in the value chain. Since the WAAM allows the repair of the rollers in the company A facilities, it avoids unnecessary transportation and reduces CO_2 emissions. Despite all these benefits, it is necessary to provide evidence of the benefits that could arise from the GSCM perspective.

4. Findings and discussion

4.1 WAAM capabilities

To answer the first research question, the expert (i.e. the general manager of Guaranteed) was asked to rank each WAAM production capability according to its level of importance for enhancing his company's performance. A five-point Likert-type scale from "1 = not important" to "5 = very important" was used. The results are depicted in Table 3.

Before going into a deeper analysis of the data, it is relevant to mention that in addition to the capabilities items proposed by Oettmeier and Hofmann (2017) (Table 1), another one emerged from the case study: "Increased equipment availability rate (proportion of uptime)". We classify this item in the "relative advantage" WAAM production capability category.

A cross-category analysis allows for identifying the WAAM production capabilities most relevant. Those refer to "relative advantage" capability and "supply-side benefits" capabilities. Based on these considerations, we put forward the following proposition:

Proposition 1. The adoption of WAAM technology supports the development of "relative advantage" and "supply-side benefits" capabilities in a company's production system.

Additionally, from Table 3 and through a within-category analysis, it is possible to identify which items within each category of capabilities most impact the respective capability.

WAAM production capabilities Category	Item	Level of importance*
RA	Cost reduction	5
RA	Improved material usage	4
SSB	Reduction and simplification of manufacturing steps	4
SSB	Elimination of pre-assembly activities	4
RA	Freedom of design	3
RA	Ability to build lightweight products	3
RA	Ability to optimise products for its function and integrate more functionality into an object	3
SSB	Reduced need for transportation services	3
DSB	Faster reaction to changing customer needs	3
SSB	Facilitated separation between product design and manufacturing tasks	2
DSB	Customised production	2
DSB	Higher customer service level	2
DSB	Production closer to the customer	2
SSB	Reduction of the supplier base	1

Note(s): Capability category: RA – Relative advantage; SSB – Supply-side benefits; DSB – Demand-side benefits
*5 points Likert-type scale from "1 = not important" to "5 = very important"

Table 3. WAAM production capabilities classified by level of importance

Table 3 shows that "*cost reduction*", "*improved material usage*", "*reduction and simplification of manufacturing steps*" and "*elimination of pre-assembly activities*" are considered to be the most important capabilities' items. The expert justifies that this is due to "*In most industries the switch from one to another manufacturing technology is cost-driven*" and because "*As the importance of CO2 emission reporting increases, customers put increasing emphasis on the careful use of critical raw materials*". Also, the potential of using WAAM to obtain new configurations for production systems and supply chains is highlighted by the expert: "*Given the pressure on supply chains and resulting long lead times, reduction and simplification of manufacturing steps is key to ensure shorter lead time*". On the other hand, items such as "*higher customer service level*", "*production closer to the customer*", and "*reduction of the supplier base*" are considered to be less important. When using WAAM to repair *in situ* metal parts, the items referring to "*reduction of the supplier base*" and "*production closer to the customer*" were not considered important for the company's performance (in this case, for Guaranteed) because there is a limited number of available suppliers for metal wire and gas. Considering the above results and taking into consideration the two most important items for each capability category, the following propositions are suggested:

Proposition 2. The adoption of WAAM enables "cost reduction" and "improves material usage", contributing to developing the "relative advantage" production capability.

Proposition 3. The adoption of WAAM enables "reduction and simplification of manufacturing steps" and "elimination of pre-assembly activities", contributing to developing the "supply-side benefits" production capability.

Proposition 4. The adoption of WAAM enables a "faster reaction to changing customer needs" and "customised production", contributing to developing the "demand-side benefits" production capability.

4.2 Impact of WAAM capabilities on the GSCM performance

The second research question concerns how the WAAM capabilities impact the GSCM performance. Questionnaire B was devised to collect the expert perceptions about those relationships. This questionnaire excluded the item "reduction of the supplier base" because it was found to not be relevant for the company under study. From Table 4, it is possible to infer how the capabilities developed through the WAAM technology impact the GSCM performance.

Table 4 shows that the "relative advantage" capability, through the items "*cost reduction*", "*improved material usage*", and "*ability to build lightweight products*", promotes an overall increase in the GSCM performance. When considering the item related to "*freedom of design*", it is possible to verify that it promotes a higher GSCM performance in the operational and marketing criteria (it increases efficiency, green/eco-design and cooperation with customers), however, it decreases the performance related to reverse logistics. According to the interviewee, this is justified because "*disassembly and recycling processes also require standardisation and volumes to reach profitable business cases. Frequent design changes will render recycling more complex*". Furthermore, considering the item's "*ability to optimise a product for its function and to integrate more functionality into an object*", the same happens: it promotes an increase in the economic/financial and operational performance and marketing performance but also promotes a decrease in the performance sub-criteria "reverse logistics. This is justified since "*especially when going to multi-material or embedded sensors, this becomes a challenge. For instance, in automotive, there are very stringent requirements for disassembly. Solutions which make this more complex would be out of these standards*". Considering the above reflections, the following proposition is proposed:

	GSCM performance criteria	Economic/ financial		Operational				Logistics		Marketing	
	Sub-criteria	Cost	Qual	Effic	Green manuf	Green desg	Green log	Rev log	Green purch	Cust satisf	Coop. w/ cust
WAAM production capabilities	RA: Cost reduction	↓									
	RA: Improved material usage	↓	↑	↑	↑	↑	↑	↑	↑	↑	
	SSB: Reduction and simplification of manufacturing steps	↓	↑	↑							
	SSB: Elimination of pre-assembly activities	↓		↑	↑						
	RA: Freedom of design			↑		↑		↓			↑
	RA: Ability to build lightweight products			↑		↑	↑		↑	↑	
	RA: Ability to optimise products for its function and integrate more functionality into an object	↓	↑	↑	↑			↓			↑
	SSB: Reduced need for transportation services	↓					↑				
	DSB: Faster reaction to changing customer needs	↑		↑						↑	
	SSB: Facilitated separation between product design and manufacturing tasks					↑					↑
	DSB: Customised production	↑	↓	↓	↓			↓		↑	↑
	DSB: Higher customer service level	↑								↑	
	DSB: Production closer to the customer	↑	↓	↓	↓						

Note(s): ↑ means that "WAAM production capability promotes the increase the GSCM performance sub-criteria"
↓ means that "WAAM production capability promotes the decrease the GSCM performance sub-criteria"
RA: Relative advantage; SSB: Supply-side benefits; DSB: Demand-side benefits

Table 4.
Relationships between WAAM capabilities and GSCM performance

Proposition 5. WAAM production capability "relative advantage" achieved through "cost reduction", "improved material usage" and "ability to build lightweight products" promotes a higher GSCM performance.

When considering the WAAM capabilities related to the "supply-side benefits", it is possible to conclude that the items included in this capability promote an overall increase in GSCM performance. Therefore, the following proposition is proposed:

Proposition 6. WAAM production capability "supply-side benefits" achieved through "reduction and simplification of manufacturing steps", "elimination of pre-assembly activities", "reduced need for transportation services" and "facilitated separation between product design and manufacturing tasks" promotes a higher GSCM performance.

The results from Table 4 also show that "demand-side benefits", considered the less important WAAM capabilities category, promote a decrease in the economic/financial, operational and logistics performance, even though those capabilities promote an increase in the marketing performance. This is due to an increase in the sub-criteria related to cost and a decrease in quality, efficiency, green manufacturing and reverse logistics sub-criteria since, according to the interviewee, "*standardisation allows costs to be compressed, customisation goes against this trend. Even if for AM design complexity comes at quasi no additional cost, the design itself will still need to be adjusted, verified and validated*" and "*standardisation also allows for standardisation of quality assurance and statistics to be elaborated*" *and also "centralised production often allows for economies of scale to be realised in terms of, e.g. purchasing, logistics. Delocalised production goes against this trend*". The item related to "*faster reaction to changing customer needs*", like the others "demand-side benefits" items, has a positive effect on the economic/financial performance and a negative effect on the marketing performance; however, and contrary to the others items, promotes an increase in the operational performance because it increases the efficiency. Considering these results, the following proposition is proposed.

Proposition 7. WAAM production capability "demand-side benefits" achieved through "customised production", "higher customer service level", and "production closer to the customer" promote an increase in the marketing GSCM performance criteria and a decrease in economic/financial, operational and logistics criteria.

The propositions were formulated based on evidence from the exploratory case study. They were developed using an inductive approach, this is from the data, we attempt to find consensus patterns and provide insights into specific WAAM production capabilities and their effects on the GSCM performance. They should further be tested by using deductive approaches and quantitative methods to validate hypotheses derived from them. Surveys and questionnaires can be clearly developed using the constructs and measurement items proposed by Oettmeier and Hofmann (2017) and Kazancoglu *et al.* (2018).

4.3 Discussion and implications

When companies decide to adopt new technologies, such as AM, they must consider the possible impact on their environmental footprint and other externalities. The GSCM includes a range of practices that should be considered and implemented throughout the supply chain with the expectation of improving a company's economic, logistics, marketing and operational performance. WAAM is a fusion-based AM technology that may contribute to enhancing the company's sustainability by improving both economic and environmental performance (Kokare *et al.*, 2022; Priarone *et al.*, 2021). However, little is still known about the impact of WAAM on the GSCM performance. This research examines the impacts of WAAM production capabilities on GSCM performance, using evidence from an exploratory case study that considers a metallurgical company whose focus is on repairing parts through WAAM technology.

From the case study, it is possible to infer capabilities brought by WAAM technology to a company's production system. The capabilities' items related to "*cost reduction*" and "*improved material usage*" are considered to be the most important. These results are aligned with the literature that pointed out the critical advantages of adopting WAAM technology (Oliveira *et al.*, 2019). Moreover, the capabilities' items related to "*reduction and simplification of manufacturing steps*" and "*elimination of pre-assembly activities*" are also considered to be crucial capabilities. Furthermore, these results corroborate the existing literature that refers to the simplification of manufacturing steps and pre-assemblies activities as one of the main advantages brought by WAAM technology (Oliveira *et al.*, 2020 and Rodrigues *et al.*, 2019a).

On the other hand, items such as "*higher customer service level*", "*production closer to the customer*", and "*reduction of the supplier base*" are considered to be less important. This is again verified in the metal AM literature (DebRoy *et al.*, 2019; Oliveira *et al.*, 2019). Overall, this research results are aligned with Naghshineh and Carvalho (2022) findings, suggesting that adopting AM technology for applications such as end-use parts or spare parts, is expected to impact the state of the supply chains in a way that improves their different capabilities).

Moreover, it is assumed that most metallic equipment can be repaired if it breaks, even if repairing is not always the most convenient or effortless activity. The possibility of repairing the equipment makes it possible to extend its useful life, avoiding not only the cost of new equipment but also disposal costs. Proper equipment preservation and repair support better equipment availability and performance. The potential of WAAM technology to repair equipment is referred to in the literature as one of its major benefits for companies (Oliveira *et al.*, 2020). Still, at the same time, there is a lack of real cases showing how WAAM is aligned with the principles of the circular economy and its contribution to optimising key activities in a company to close the material and resources cycles. This research highlights that most of the capabilities acquired by WAAM technology in a company's production system have a positive influence on the GSCM performance dimensions. The results show that "relative advantage" capability's items such as "*cost reduction*", "*improved material usage*", and "*the ability to build lightweight products*" may contribute to the promotion of higher GSCM performance. Furthermore, "supply-side benefits" such as "*reduction and simplification of manufacturing steps*", "*elimination of pre-assembly activities*", "*reduce the need for transportation services*", and "*facilitated separation between product design and manufacturing*" may also contribute to higher GSCM performance.

Seven propositions derived from the case study results that support the adoption of WAAM technology as an enabler in implementing GSCM practices. These results are aligned with the existing literature concerning AM technology and GSCM, in which it is emphasised that companies adopt AM technology for considering different environmental, social and economic performance benefits (Torres *et al.*, 2020). Namely, WAAM's ability to optimise resources within the supply chain enables a product with a more flexible design and contributes to costs and time reduction.

This research gives an interdisciplinary view of the problematic of WAAM adoption and its impacts on the varying aspects of GSCM performance. It offers to logistics researchers a set of propositions to pursue further studies in this under-explored logistics management research area. Also, it provides to metallurgical researchers and technology developers with an overview of the real impact of the WAAM in productive systems, giving indications for future research avenues. The results provide insights to managers on how companies could adopt new and disruptive technologies such as WAAM to develop unique and not imitable production capabilities to obtain a competitive advantage compared to their competitors. Also, the research shows that the benefits of WAAM adoption need to be explored in a broader context, spanning from the company's internal operations to the upstream (i.e. customer side) and downstream (i.e. supply side) tiers of their supply chain. Companies in different industries take GSCM as a way to pursue to increase their performance, but also to meet the institutional or stakeholder pressures. The results from this research suggest that the adoption of WAAM generates some trade-offs in GSCM performance, so there is a need to carefully evaluate the industrial context in which WAAM technology is deployed.

5. Conclusion

In this research, a theoretical framework was developed to assess the impact of adopting WAAM technology on GSCM performance. WAAM can be used to repair and refurbish obsolete products and to extend the product's life span instead of manufacturing new ones. These two aspects can generate significant cost savings for a company, e.g. by reducing the need to store spare parts. The case study carried out within this research highlighted the WAAM production capabilities related to "relative advantage" and the "supply-side benefits". A new WAAM capability emerged from the case study: the "increased equipment availability rate (proportion of uptime)"; this is a relevant capability that was not mentioned until now in state-of-the-art. Seven propositions were devised from the case study findings, and overall, it is possible to conclude that WAAM technology is expected to support GSCM performance. However, some trade-offs arise in GSCM performance criteria, for example, "demand-side benefits" brought by the adoption of WAAM, such as "customised production", "higher customer service level" and "production closer to the customer", have a negative effect the economic/financial, operational and logistics GSCM performance. This is due to delocalised production and customisation that goes against the trend of compressing costs and economies of scale that are possible with standardisation. Also, products produced by WAAM still need to be regulated and certified.

This research faces several limitations. A single case study research design was chosen, and only one expert, i.e. the company manager, was questioned. This research design could create bias, but it also provides a depth understanding of the phenomena under study. Therefore, a multiple-case research design covering a cross-country analysis is suggested as future research work. The propositions derived from this research need to be further tested in a quantitative analysis to find out possible statistical relationships between WAAM capability and GSCM performance. To this end, the constructs and measurement items from Oettmeier and Hofmann (2017) and Kazancoglu *et al.* (2018) could be used. Additionally, the conduction of a longitudinal study is suggested for future research work so that the accuracy of the results from this research can be examined over time.

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Appendices

Questionnaire A

Questionnaire protocol

This questionnaire aims to support research on the influence of **wire and arc additive manufacturing** (WAAM) on **green supply chain management** (GSCM) performance.

A WAAM capability is a factor that affects the decision to adopt WAAM technology. WAAM technology adoption promotes innovations at process and operation levels that could impact the company performance. Therefore, in this questionnaire, we pretend to understand the importance of WAAM capabilities that are acquired in the company's production.

Your contribution is very important to the development of this study. Please accept to collaborate with us and fill out the following questionnaire.

Indicate **your perception about the importance of each WAAM production capability for enhancing the company's performance.** Using a Likert scale from "1 = Not important" to "5 = Very important" and mark with X the answer which suits the best.

WAAM Capabilities	**1** Not important	**2**	**3**	**4**	**5** Very important
Cost reduction	☐	☐	☐	☐	☐
Improved material usage	☐	☐	☐	☐	☐
Freedom of design	☐	☐	☐	☐	☐
Ability to build lightweight products	☐	☐	☐	☐	☐
Ability to optimise products for its function and integrate more functionality into an object	☐	☐	☐	☐	☐
Reduction and simplification of manufacturing steps	☐	☐	☐	☐	☐
Elimination of pre-assembly activities	☐	☐	☐	☐	☐
Reduction of the supplier base	☐	☐	☐	☐	☐
Reduced need for transportation services	☐	☐	☐	☐	☐
Facilitated separation between product design and manufacturing tasks	☐	☐	☐	☐	☐
Production closer to the customer	☐	☐	☐	☐	☐
Customised production	☐	☐	☐	☐	☐
Faster reaction to changing customer needs	☐	☐	☐	☐	☐
Higher customer service level	☐	☐	☐	☐	☐

Questionnaire B

This questionnaire aims to support a research about assessing the impact of **wire and arc additive manufacturing** (WAAM) adoption on **green supply chain management** (GSCM) performance.

GSCM has emerged as an organisational philosophy or tool by which organisations and their partners achieve corporate profit and market-share objectives by reducing environmental risks and impacts while improving ecological efficiency. GSCM performance measurement has great importance in implementing effective GSCM and integrates different dimensions such as economic/financial, logistics, operational and marketing. In this questionnaire, we aimed to examine the impact of each capability achieved with WAAM adoption on the GSCM performance.

Your contribution is very important to the development of this study. Please accept to collaborate with us and fill out the following questionnaire.

Impacts of adopting WAAM technology on GSCM performance

In the following matrix, **sign your perceptions about relationships that you believe exist between the WAAM production capabilities and GSCM performance** criteria, indicating if each WAAM production capability promotes the increase or decreases each one of the GSCM performance sub-criteria. Consider the measures bellow for each GSCM performance sub-criteria. Use the following notation:

↑ – WAAM production capability promotes the *increase* the GSCM performance sub-criteria
↓ – WAAM production capability promotes the *decrease* the GSCM performance sub-criteria
N/A – not applicable

	Economic/ financial GSCM performance sub-criteria		Operational				Logistics			Marketing
WAAM capability	Cost	Quality	Efficiency	Green manufacturing	Green/ Eco design	Green logistics	Reverse logistics	Green purchasing	Customer satisfaction	Cooperation/ Collaboration with customers
Cost reduction										
Improved material usage										
Freedom of design										
Ability to build lightweight products										
Ability to optimise products for its function and integrate more functionality into an object										
Reduction and simplification of manufacturing steps										
Elimination of pre-assembly activities										
Reduced need for transportation services										
Facilitated separation between product design and manufacturing tasks										

(*continued*)

	Economic/ financial GSCM performance sub-criteria			Operational			Logistics			Marketing
WAAM capability	Cost	Quality	Efficiency	Green manufacturing	Green/ Eco design	Green logistics	Reverse logistics	Green purchasing	Customer satisfaction	Cooperation/ Collaboration with customers
Production closer to the customer										
Customised production										
Faster reaction to changing customer needs										
Higher customer service level										

GSCM perf. Sub-criteria	Examples of measures	GSCM perf. Sub-criteria	Examples of measures
Cost	Costs (procurement; transportation cost; manufacturing cost; cost of raw materials	Green logistics	Average load on laden trip (weight/volume); on time delivery; mode of transport; just in time for logistics
Quality	Customer rejection rate; continuous improvement system; scrap rate; rework rate	Reverse logistics	Remanufacturing of materials; design for reverse logistics; reusing and recycling of materials
Efficiency	Operation expense, capacity utilisation; energy efficiency; overhead expense	Green purchasing	Supplier support; providing design specifications for green purchasing
Green Manufacturing	Redefine operation/production processes; use of recyclable/recycled materials; structure for easy disassembly; reduction in operations steps; structure for easy assembly	Customer satisfaction	Service response rate; customer returns; number of customers retained
Green/Eco Design	Reused and recycled materials in new designs; longer service/product life; design for remanufacturing; cooperation with customers/suppliers for eco-design	Cooperation/Colla-boration with Customers	Sharing common goals with customers; cooperation with customers to decrease environmental impact of operations