Energy management in manufacturing: Toward eco-factories of the future – A focus group study

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The integration of environmental sustainability and eco-efficiency has been recognized as a means to fos-ter economic and environmental performance, increase competitiveness and use it as a lever to spur inno-vation. Besides integrating green technologies in the manufacturing system, putting environmental goals on the company agenda, and pursuing green norms and directives, the question is: quo vadis eco-factory?Based on a focus group study with 22 European experts and high-level representatives from industry, policy-makers and academia, we raised the question of what might be the research directions and solu-tions for eco-factories in the next 20 years. Our two major findings suggest that (i) research should more focus on the opportunities that human participants in a manufacturing system can foster change toward eco-factories and that (ii) firm-intern characteristics like enabling environmental capability, organization and structure will likely determine upon successful transition and increased competitiveness.

Keywords: Energy efficiency, Sustainability, Eco-factory, Focus group, Energy management, Production

H I G H L I G H T S

- The paper aims at introducing the way toward eco-factories of the future.
- A focus group study is conducted with 22 European experts.
- We highlight research directions and solutions for eco-factories in the next 20 years.
- Human participants in a manufacturing system can foster change toward eco-factories.
- Firm-intern characteristics determine successful transition and competitiveness.

1. Introduction

Energy and resource consumption are of major focus for industry, policy-makers, and society. The European Commission has raised concerns on energy consumption grounded on climate change and supply security. While ecological consequences like global warming and resource depletion are driven by consumption behavior and rate, supply security involves severe political and social risks [1]. Consequently, the European 2020 strategy defined targets for the 20% reduction of primary energy consumption and related carbon emissions while maintaining the competitiveness of European companies [2]. Together with households, commercial and transportation, manufacturing is one of the major contributors to energy and resource efficiency. According to the IEA, the manufacturing industry accounts for 37% of the global primary energy consumption 3. In Europe, 40% of the electricity consumption accounts to manufacturing, while industry is responsible for ca. 30–40% of the total GHG emissions [4]. Manufacturing units and factories therefore play a critical role in achieving these targets. A factory as a socio-technical system combines factors such as labor, material, energy, information and machines for the purpose of value creation in forms of products and services. While a significant part of energy and resources are used to create value, significant parts are wasted in terms of emissions, heat, and other losses.

Several studies emphasize on the improvement potential in industry. The Energy Efficiency Policy Recommendation of the International Energy Agency [5] identifies potential savings of ca. 18.9 EJ/year and 1.6 Gt CO_2/year in industry by the year 2030. The consultation group "Smart Manufacturing" foresees a saving potential of 10–40% at European level and highlights the importance of

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ICT (Information and Communication Technologies) as an enabler for energy efficiency [6].

Within the European Union, different initiatives within the European Technology platforms (ETP) have guided the process of defining and scoping relevant research topics. Examples are EuMat (European Technology Platform for Advanced Engineering Materials and Technologies), the Green Car Initiative, ACARE (Advisory Council for Aeronautics Research in Europe), ERRAC (European Rail Research Advisory Council), or ERTRAC (European Road Transport Research Advisory Council). These directions for research have been also documented and reflected in the scientific community [7,8].

There are different and sometimes contradictory thoughts and focus in academia and industry concerning the enabling factors for a shift toward eco-factories as well as its main pillars. Yet there is no clear definition or consensus on what could constitute these clean and competitive eco-factories of the future. The way to achieve eco-factories is interpreted differently by academia, industry and policy-makers hence leading to diverse approaches and solutions.

Bridging the energy management *knowledge gap* between different actors (i.e. academia, industry and policy-makers) on the way to shift toward eco-factories is a major aim of the paper. In that regard, industrial and policy needs in these areas are analyzed based on a focus group study and contrasted with the concepts proposed in the pertinent literature. Guided by this knowledge gap, the article takes a leap forward and provides research directions for eco-factories, i.e. manufacturing systems with the aim to build competitiveness upon sustainability and especially environmental practices. Besides, the paper strengthens the theoretical base needed for energy-based decision making in manufacturing industry.

The overarching research question is: "What are solutions and research directions for eco-factories in the next 20 years"? It is aimed to involve a multi-stakeholder perspective to grasp demands and directions not only from the industry, but also from policy-makers, industry associations, research centers, and academia. In this context, we have consulted three major European companies within the transport manufacturing industry as well as 22 experts from industry, academia and policy-makers to provide a long-term perspective and to introduce the step afterwards to truly establish clean and competitive eco-factories. The purpose is to spur debate in the research field and to identify important research areas from diverse perspectives. While a traditional literature review with content analysis is meaningful to investigate the current state of the art and may identify research gaps, this approach is especially worthy twofold: (i) pointing out demands from the stakeholders and (ii) highlighting fields for academia-practice knowledge transfer.

The paper is structured as follows: the next section provides an overview of research background of the field. The third section presents the methodology and Section 4 illustrates the traditional eco-manufacturing system framework. Section 5 is dedicated to present the results. In Section 5.1, we investigate the major obstacles and enablers toward eco-factories by means of literature search and survey in three companies. Sections 5.2 and 5.3 present future research paths for eco-factories developed by a high-level focus group and highlights main issues that should be on the research agenda in the next 20 years. Finally, Section 6 concludes the paper by providing theoretical and managerial implications of the study as well as an outlook for further research.

2. Background

In recent years, there have been quite many research initiatives aimed at creating clean and competitive eco-factories. Below, some of these endeavors are explained in brief.

At global level, many scientific papers focused on drivers for and barriers to energy management in production [9,10,10–13] while other recent studies introduced and analyzed the role of strategic paradigms for improving energy efficiency in manufacturing [14–23]. In this regard, Thollander et al. [10] analyzed the stimuli for improved energy efficiency in European energy intensive foundry industries, and highlighted the importance of finance related and organizational drivers. In a similar context, Trianni et al. [11] investigated the barriers to energy efficiency. Backlund et al. [19] emphasized the importance of including energy management practices in future energy policies to increase the energy efficiency potential level thus achieving energy saving targets for 2020 and 2050, particularly in manufacturing industries.

On a more disaggregated level, studies have focused on developing a radically new paradigm for cost-effective, highly productive and energy-efficient production systems by modeling and optimizing energy consumption in factories aimed at moving the manufacturing industry toward a more resource-efficient and low-carbon future [24–31]. In particular, a cluster of these studies concerned manufacturing process paradigms that includes articles related to innovations, changes and diverse proposals for redefining the manufacturing processes inside a company or a determined industry sector by the development of new technologies, with the aim of reducing the environmental impact related to the energy consumption on the manufacturing processes [32–38].

Another group of studies focused on performance monitoring and control mechanisms toward achieving eco-factories of the future [39–50]. In that vein, May et al. [39,51] proposed a new method to develop company specific energy-related key performance indicators which support identification of energy efficiency improvement areas and associated action plans for achieving energy saving targets in a manufacturing facility also considering the synergies and trade-offs with other production performance indicators. Previous papers on the subject focused on energy efficiency measures, standards, labeling regulations, metrics and performance measurement on a national and policy level or developed generic metrics for the benchmarking of energy-related performances of manufacturing plants.

Another set of research work developed tools and methods on the way to achieve eco-efficient manufacturing [24,29,51–55], and many scholars stressed out the role and use of Information and Communication Technologies (ICT) as a significant enabler of energy management in manufacturing [56–61].

All in all, a variegate set of approaches and tools have been developed as part of several research attempts. Thus, implementation of these proposed approaches and solutions could contribute to a more efficient and environmentally conscious production at industry for creating clean and competitive eco-factories of the future. The real challenge at this point is to utilize all this knowledge for going toward a holistic consideration and joint implementation of different concepts also considering synergies in-between, aiming to achieve a global optima of target performances in production facilities.

Therefore, this paper is built upon the insights and key findings derived from the established initiatives in industry and research, and aims at introducing the way toward clean and competitive eco-factories.

3. Methodology

The research design follows an inductive approach using qualitative data collection and analysis methods. To address the aim and research questions appropriately, we followed a two-step research design approach as shown in Fig. 1.

The first step is identification and analysis of concrete drivers and challenges. Here, we used a traditional literature review with content analysis and structured survey questionnaire for qualitative and quantitative data gathering in three companies in the rail, automotive and aerospace industry. This preliminary step was intended to account for the current situation in industry and state of the art in academia, and to spur debate and input for the subsequent research action and discussion. Hence, the second step is built around the focus group methodology with the aim to identify potential solutions and herewith research demand and future research directions. The driver and challenges identified in the first step were used as discussion stimuli in the focus group exercise.

3.1. Literature review

The starting point for the research was a literature review using content analysis on the topic of energy- and resource efficiency in manufacturing. The objective of the literature review is to summarize and evaluate the current state of the art on drivers and barriers for eco-factories. Hence, the research question underlying the review is "*what are drivers and barriers for eco-factories?*". The process of content analysis was used to provide the analysis with a structured approach [62,63]. The material collection was based on journal articles available via the Scopus and Web of Knowledge databases. We used a combination of the terms "energy efficiency" and "manufacturing" in article titles, abstracts and keywords to identify a first stock of papers published in the last 20 years (i.e. from 1995 until 2015). The search yielded 3008 results. These papers were subject to two filtering processes: (i) using ca. 30 keywords to search in the results itself and (ii) assessing the articles according to title and abstract reading. Criteria for assessing the suitability of papers in the field were: (a) focus on manufacturing industry, (b) focus on energy efficiency, and (c) only studies that are written in English. The filtering process resulted in 359 suitable journal papers. Through an inductive process of reading the articles, a classification scheme emerged around the following classes: barriers and drivers, information and communication technology; strategic paradigms; supporting tools and methodologies; manufacturing process paradigms; and manufacturing performances in trade-off. Each of these identified classes represents the core aspect that a paper is dealing so that each paper can be definitely ordered in only one class. Eventually, 42 papers were classified into drivers and barriers which were subject for further analysis and research direction.

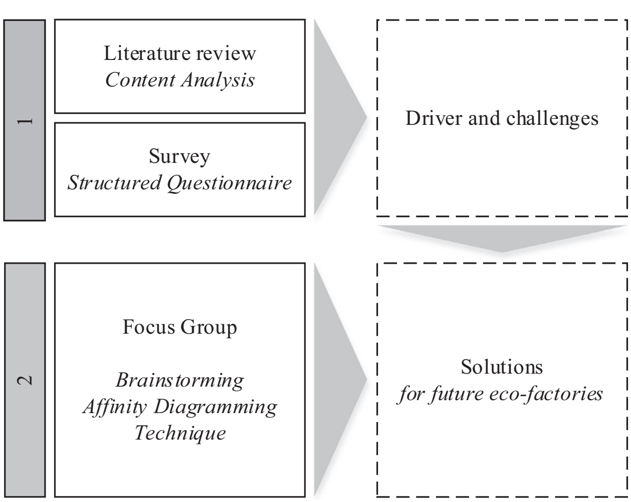


Fig. 1. Research approach.

3.2. Survey

Each survey participant company were informed by 2–3 researchers in a physical meeting about the prospective research, where the major areas for investigation were also defined in collaboration with the companies which are listed in Table 1. The questionnaire was then detailed by the researchers and sent via email to a contact person in the company. The contact person was asked to distribute the survey to the persons in charge for the major areas, collect their answers and provide it back to the researchers. The survey contained information about the production environments, i.e. type and procedures of productions system, production planning, plant location and layout, applied manufacturing technologies and processes, information systems, and energy- and resource-related issues.

3.3. Focus group

The focus group method has a long tradition in social sciences and especially marketing research [64], whereas traditionally quantitative techniques have been favored by the production and operations research community. However, as the ultimate purpose of the focus group method is to discuss in depth on a certain topic to extract novel insights and expert knowledge, its usage and application in the field of manufacturing is highly valuable.

The focus group method served as an extension to the preceding literature review and survey, with the aim to develop solutions for current and future barriers and challenges for eco-factories. It has an exploratory nature, i.e. to critique and balance findings from literature and survey, to explore multi-stakeholder views, and to open directions for future research.

Experts in the field were contacted by email by the researchers with an invitation to participate in the focus group discussion. The experts were chosen based on suggestions and discussions with EFFRA and the World Manufacturing Forum. It was aimed for a homogenous group based on expert knowledge and heterogeneous based on represented type of organizations. It was aimed to include representatives from four major areas in the focus group discussion, i.e. industry, academia, policy-makers, and research associations and centers. Finally, 22 participants (as listed in Table 2) were present at the workshop.

Ten different European nations were represented, whereas 3 participants were representing the body of the European

Table 1
Survey participants.

Company	Description	Interviewee
Company A	• Rail industry • Division with 3000 employees • Facilities spread worldwide	Corporate Technology Researcher Factory planner Sustainable Production Engineer
Company B	• Supplier of industrial automation for automotive industry • 9 production facilities worldwide • More than 10,000 employees	Head of Advanced Engineering; R&D Manager Automation Engineer
Company C	• Design, manufacturing and assembly of high technology aero structures, engine components and mechanisms for Aeronautical sector • 1000 employees and over 100 Million Dollar turnover • Four manufacturing facilities in Spain	General Director Head of Technical Office; Continuous Improvement Responsible

Table 2
Participants structure in focus group.

Position	Area of organization	Country
Advanced Research Manager	Industry	Italy
Director	Research Center	Italy
Research Program Manager	Policy	EU
Project Manager	Industry	Spain
Research Coordinator	Research Center	Finland
Deputy Head	Policy	EU
Chairman	Policy	Switzerland
Chief Operating Officer	Industry	Finland
Director	Research Center	Spain
IS Manager	Industry	Slovakia
Manufacturing Director	Industry	Denmark
Policy Officer	Policy	EU
Senior Researcher	Academia	Denmark
Assistant Professor	Academia	Poland
International R&D Projects Director	Industry	Spain
Senior Researcher	Academia	Germany
Environment Technician	Policy	Denmark
Full professor	Academia	Sweden
Manager – R&D and Public Affairs	Industry	Italy
Director	Research Center	Italy
Senior Engineer	Industry	Italy
Project Manager	Research Center	Sweden

Commission. There were 8 participants from industry, 5 from research centers, 5 from policy-makers, and 4 from academia.

In the preparation of the focus group workshop, the participants were sent a short summary of the results of the literature review and survey, and the following question was communicated as the main focus of the workshop: "Which solutions and research directions should we consider in the next 20 years with regards to our factories?". The workshop was scheduled for four hours, whereas 1.5 h were dedicated to kick-off presentations, welcome round and participant introduction. The remaining time was explicitly used to discuss about the proposed research question. The discussion was facilitated by a structured brainstorming round with the question above in focus [65]. First, all contributions were collected on paper, whiteboards and flipcharts without any critical evaluation. Afterwards, we employed Affinity Diagramming technique [66] to categorize all items. In this process, the participants had to clarify and augment their points as well as their categorization approach. The focus group workshop ended with a wrap-up of the results. Workshop results were documented by notes and photos, and were condensed afterwards by the research team in a report which was made available to all participants.

We followed principles of conduct according to Axelrod for the focus group discussion to facilitate scientific rigor as illustrated in Table 3 [67].

However, we did not limit our number of participants to 8–12 as mostly suggested in literature, but allowed a doubling of the group. This was done due to two reasons: (i) a significant number of participants was required to represent the major target areas of organizations as well as some good representation of the European community and (ii) the focus of the research, namely the strategic forward looking to future solutions for eco-factories seemed to be more successful if we include more experts with substantial experiences, inspiring ideas and visionary thoughts.

4. Traditional eco-manufacturing system framework

The manufacturing system has enlarged its boundaries from the factory door to a much wider space. Energy- and resource efficiency undoubtedly plays an important role in the production facility itself, but factories' eco-system is crucial for the determination of factors and receiver of effects at the same time. Fig. 2 represents the major energy and resource consumers in the factory and determining factors around the factory and the external as well as internal parameters that lead to variations in consumption behavior.

To produce goods and services of the right quality and quantity at the right time and right manufacturing cost, manufacturing processes are responsible for the major share of energy and material consumption on the one side, but on the other hand for the value creation and extension. The consumption patterns are partially dependent on the machine and/or operator's behavior and are dynamic based on the machine's energy states. A detailed analysis of the machine's behavior and the development of energy-related key performance indicators (e-KPIs) reveal options for improvements.

A further element inside the factory are the technical building services (TBS) that deal with heating and cooling of spaces or processes, ventilation and air conditioning, power engineering or media supply and treatment. TBS systems enable and provide the production system with the required energy in the required medium. The total energy consumption by TBS of a factory can add up to ca. 30% and is therefore the hotspot for improvements. Main levers for improvements are generally equipment design, equipment control, and avoidance of losses. The TBS system and production machines are complemented by the building shell for energy efficiency considerations. Energy efficiency of buildings has been on the research agenda in civil engineering much longer than energy efficiency has found its way into production engineering. Improvements in insulation, roofs, walls or windows together with sophisticated ventilation concepts are major sources for predetermining energy efficiency opportunities.

Planning of production systems is not limited solely to investment decisions based on short term effects anymore, but the strategic decision making process dictates that considerations be

Table 3
Research quality management.

Principle	Measure(s)
Clearly understood objective	Objective communicated in invitation and workshop and agreed upon in the introduction of the workshop
Effective recruiting of participants	Identification of experts in the area through the support of EFFRA and World Manufacturing Forum
Homogeneity within group	All participants have expertise and extensive experience in sustainable manufacturing
Active listening	Usage of brainstorming and affinity diagram technique to structure focus group and facilitate participant contribution
Well-prepared moderators	Preparation by literature review and industry to structure focus group
Free flowing dialogue	Usage of brainstorming and affinity diagram technique to structure focus group and facilitate participant contribution
Restrained group influence	Declaration of data confidentiality regarding participants; encouraging contributions by mentioning multi-stakeholder perspective
Competent researchers	Research team led by full professor of advanced manufacturing system

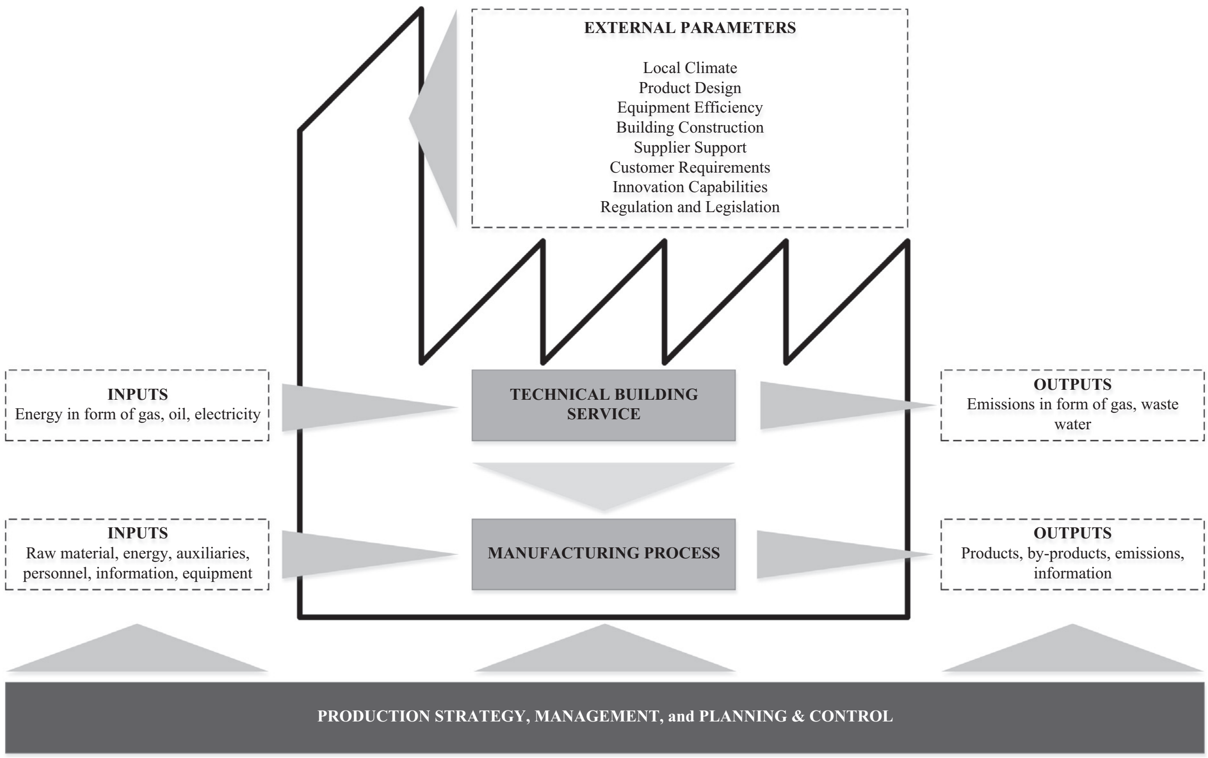


Fig. 2. Manufacturing system framework.

also given to long term impacts (e.g. eco-efficient plant design and management). In that vein, production management could have effects on manufacturing systems both on strategic (e.g. plant layout) and operative (e.g. operative production planning and control, production scheduling, resource allocation) decisional levels. Thus, a strategic objective of shifting toward eco-factories could only be truly achieved by a strong connectivity and integration of the strategic layer with production management, and production planning and control layers, altogether affecting the design of the ultimate eco-efficient production system.

5. Results and discussion

In this section, we provide the results of the research work based on the insights and key findings from our literature review, survey and focus group studies as explained in the methodology section. Building upon the traditional eco-manufacturing system framework illustrated in Section 4, the following subsections (i) analyzes and highlights common drivers for and barriers to eco-efficiency in manufacturing (Section 5.1), (ii) defines and explains the changing paradigms in the manufacturing context (Section 5.2), and thus (iii) demonstrates the main pillars to shift toward clean and competitive eco-factories of the future (Section 5.3).

5.1. Drivers and barriers

Developing strategies to integrate environmental sustainability into manufacturing is of utmost importance to gain competitiveness. Successfully implementing energy and resource efficiency programs, pollution prevention and control programs, or sustainability initiatives is of urgent need. The definition of strategies for strategic initiatives, the development of action plans and measures and finally the implementation of environmental-oriented programs is supported or hindered by barriers and drivers that can have different characteristics. Barriers are considered as factors that inhibit a decision or behavior that appears to be both environmentally and economically efficient [68]. Meanwhile, drivers are the stimuli for environmental manufacturing which are the main reasons for industrial companies to implement e.g. energy efficiency measures in manufacturing.

The efficiency gap describes the phenomenon that e.g. cost-effective energy efficiency measures are not implemented [69]. Although economic reasons might spur initiatives to environmental efficiency, barriers hinder the implementation in the industrial practice. Literature and practice refer mainly to three categories of barriers, i.e. economic, institutional and organizational barriers. In a more detailed analysis, Cagno and Trianni [9] mention additionally awareness-related, behavioral, competence-related, information-related and technology-related barriers beyond the aforementioned three main categories.

Market failure can occur due to a variety of reasons e.g. an ineffective allocation of goods and services by the market [70] and includes imperfect information, split incentives and the principal agent problem, among others [71,72]. Imperfect information relates to insufficient information about the energy performance of different technologies and its potential savings. Imperfect information also covers lack of information regarding energy consumption patterns, energy performance of equipment, poor information quality, lack of staff and management awareness and lack of technical skills [73–76]. Furthermore, incomplete information and information asymmetry for analysis of investments projects are argued to lead to sub-optimal decisions which require more rigid performance measurement and analytic and discussion-oriented investment project culture [77]. Split incentives refer to a condition where two parties have different incentives for their actions. If a person or department cannot gain benefits from environmental programs it is likely that implementation will be of less interest affecting the energy efficiency decisions.

Similarly is the principal agent problem which arises due to lack of trust between two parties at different levels within society or a business organization. In fact, in a study performed in UK's process industries, stakeholders determined that return on investment is a main problem for undertaking energy efficiency improvements due to distrust of managers and their orientation toward short payback times [78]. It is of utmost importance to select appropriate strategies aligned with the corporate goals for achieving eco-innovation. The current shift of the manufacturing industry toward eco-efficiency is in fact a social dilemma since companies or specific agents (e.g. plant managers) could focus on specific targets on certain outcomes in short and medium terms thus ignoring the environmental and social aspects of sustainability which could bring long-term benefits (e.g. image improvement, new market opportunities, etc.) to the firm [79,80]. Therefore, this dimension should be carefully addressed using competent theoretical frameworks, e.g. evolutionary game theory [81].

Economic barriers, also when the market is functioning can still be present. Among these barriers are included hidden costs, risks, access to capital and heterogeneity. Hidden costs refer to the cost of production disruptions, overhead costs, lack of time for the search of energy efficiency measures, the cost of identifying and analyzing the cost-effectiveness of opportunities and other priorities for capital investments due to production-related investments having higher priority [82]. Risk refers to the potentiality of disruptions in the manufacturing system mainly due to technical causes. In fact, there is a study that considers that these kinds of barriers may not be overcome by market-related public policy instruments but is rather a consequence of how the energy issue is organized within the firms [83]. Lack of access to capital also represents a relevant barrier for companies because it is a pre-requisite for carrying out the investments. Finally, heterogeneity refers to the wide applicability of an environmental technology. While an environmental technology can be cost-effective in the mean, it is not profitable for all firms.

The economic barriers play an important role in the energy efficiency investments and the majority of the scholars place it as one of the main barriers to be overcome. Nevertheless, there are some studies that affirm that despite its importance, the most determinant factors of firm's investment behavior and outcomes are organizational and institutional [84].

The institutional barriers refer to factors enforced by organizations holding mandatory power, normative pressure from the industrial association and the public, and pressure exerted from the industrial sector [85]. Between the institutional barriers may be the lack of integration of energy and environmental issues during policy formulation, the non-existent standards for energy-efficient products/processes resulting in addressing symptoms of energy problems rather than reaching the root of it. Also, the administered and distorted energy pricing can be a barrier to energy efficiency improvement initiatives and the non-existent "carrot and stick approach" to punish the inefficient and reward the efficient firms which leads to an indifferent attitude of firms toward energy efficiency. Furthermore, the lack of strict enforcement of the existing regulations and improper implementation of policies and programs may also result in making these barriers strong [86]. Analysis also suggests that future energy conservation policies should provide industries with relevant incentives to promote the adoption of energy saving investments, and that these plans need to be differentiated with regard to industries' specific characteristics [87].

Organizational barriers may refer to the firm's structure, i.e. physical or less tangible such as the existent capacity to trade heat or electricity or the interaction level of the firms with R&D institutions and universities. Further typical organizational barriers are the firm's culture and learning capacity as well as behavioral factors like values and attitudes. Organizations may encourage energy efficiency investments by developing a culture characterized by environmental values with a clear environmental strategy that is known to all the members of the company and complemented by a higher managerial commitment [85]. Thollander et al. [10] suggests commitment of top management, long-term energy strategy and people with real ambition as important organizational driving forces among others (e.g. company's environmental profile, network within the company, improved working conditions, etc.).

On the other hand, studies affirm that the environmental performance improvement of a firm is a dynamic process highly related to the abilities of all the firm's members not just managers; thereby it is necessary to enhance the employees' ability to implement new environmental approaches by encouraging practices such as self-learning, professional education and job training. This last statement is also supported by Sola and Xavier, who affirmed that there is a strong relation between the organizational human factors and the level of energy losses in the organizations and the improvement of these through mechanisms such as education and training can contribute to the elimination of these barriers [88].

Typical market related concerns for economical savings and productivity raises are reduction of the product cost and higher productivity in the production processes resulting from lower energy use, but also the threat of rising energy prices and international competition are identified [10,69]. Further levers for environmental benign manufacturing are energy service companies and third party financing [89,90].

Policy related drivers pertain to governmental programs, incentives and subsidies. These also include regulatory and financial incentives that support the improvement measures and foster a faster return on investment, subsidies for energy efficiency technologies and offering detailed support from energy experts when implementing energy efficiency investments [91].

The culture-related drivers are encouraged by the organization's environmental management, attitudes and values toward energy efficiency. Schönsleben et al. found, for example, that employees' knowledge acquisition and awareness was an important driving force [92]. Other drivers include managers' commitment and motivation, people with real-ambition, which is closely linked to personal commitment of managers, long-term energy strategy, and environmental management systems.

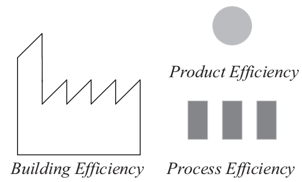
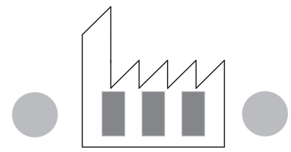
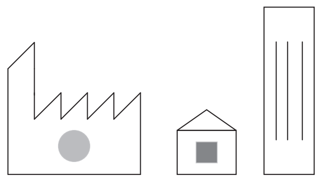
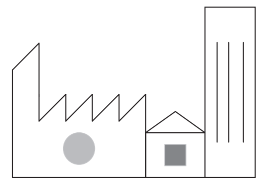
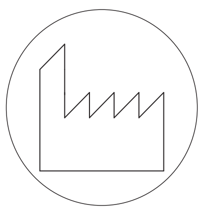
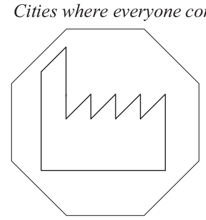
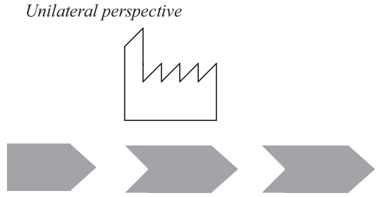
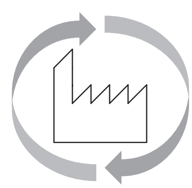
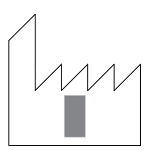
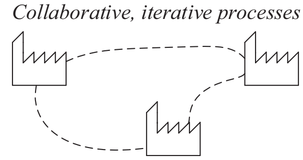
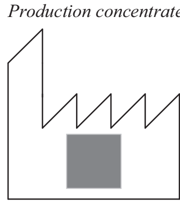
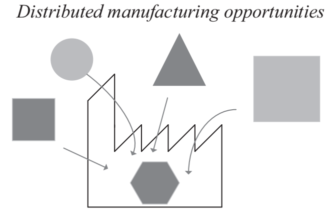
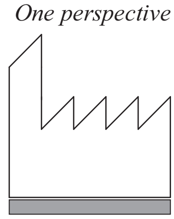
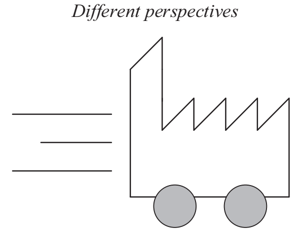
The majority of the studies converge in identifying the market-related drivers as the most relevant for energy efficiency investment with the reduction of the product cost the most significant. Nevertheless, this statement does not seem to be applicable for SMEs, where the main business objective for the implementation of energy efficiency practices was found to be the potential for improved quality, efficiency and reduced waste and not the opportunity to reduce cost [93].

5.2. Changing paradigms in manufacturing

Europe's manufacturing sector has to change shifts regarding approaches and attitudes to manufacturing systems for boosting its competitiveness. Creating opportunities through the energy – and resource aware factories is key to support corporate strategy and to spur innovation. New changing paradigms comprehend the 360-degree makeover of factories, from shop-floor to supply chain, from blue collar staff to top management, from employee to stakeholder. The objective of eco-factories is to enable clean and competitive manufacturing systems irrespective of factories' location or size, and to find opportunities based on sustainability issues to grow beyond their borders. Ecology in manufacturing has become paramount in recent years and leads to a changing manufacturing world as shown in Table 4.

Increasing environmental concerns have reached the middle class, and companies now understand that the consumer interest

Table 4
The 7 paradigm shifts.

Paradigm	Today	Tomorrow	Description
Holistic thinking	 Product Efficiency Building Efficiency Process Efficiency	 *Efficiency of the whole system*	• Consumer interest in green products • The necessity to understand, analyze and improve the whole system
Intelligent cities	 *Seperate work and life spheres*	 *Cities where everyone comes together*	• People working and producing from home • Increased awareness of community stakeholders in the factories and production • Resource and energy efficiency of the whole city
Interdisciplinary focus	 *Unilateral perspective*	 *Multilateral perspective*	• No standard KPIs • No standard approach that focuses on the whole system • No integrated tools to support analysis and decision-making
Integrative view	 *Design, produce, sell*	 *Collaborative, iterative processes*	• Design and production merging together with sales in a continuous cycle • Collaborative product development based on crowed sourcing • Using life cycle perspective to the factory
Cloud manufacturing	 *Production concentrated on one site*	 *Distributed manufacturing opportunities*	• Production using additive technologies • Flexible small scale production • Production networks that can be connected on demand
Consensus building	 *One perspective*	 *Different perspectives*	• Bringing different stakeholders with different interests and goals together • Constraints from new legislations and regulations
New infrastructure requirements	 *Stiff infrastructure*	 *Flexible infrastructure*	• Different requirements on the factory infrastructure (e.g. smaller, mobile or temporary structures) • New logistics concepts

in green is developing. Findings of the EURO RSCG Worldwide study suggest that more than 70% of consumers shop more carefully and more than 50% are concerned about a detaching of societal behavior and natural world. In the same study, more than 60% of respondents declared that making environmental friendly choices makes them feel good [94]. The discussion around climate change has deliberately fueled the understanding and issues about environmental considerations also in industry. Mass media and Hollywood have produced a more sensitive incorporation for environmental awareness. The Nobel Prize for the IPCC and an in general changing life style is driving these concerns even more. The company is not viewed as a standalone entity anymore, but as a vital part of a larger system which needs to be optimized in consideration of all levels.

Advanced manufacturing and information technologies can provide new stimuli for increasing efficiency, but also leveraging on competitive advantage. Additive technologies provide opportunities with new materials to re-engineer and re-invent manufacturing processes. The focus should be on the improvement of existing technologies in terms of efficiency and on the other hand on the development and implementation of new technologies to take the next leap forward. Particularly, the combination of manufacturing and information technologies is gaining importance. Additive forming for example has reached the possibility of metal forming and is moving from mostly rapid prototyping applications to real manufacturing environments. The integration of smart machines with embedded smart devices operating in wireless networks leads to a quantum leap in quality and precision. The interplay between hardware and software, using embedded systems and wireless technologies is currently spreading in high-flexibility manufacturing environments. The digital factory has brought tremendous changes in the considerations of product and manufacturing system design. Virtual reality is gaining importance in manufacturing. High-resolution simulation models of factories in connection with real-time data gathering and processing are already available as prototypes for new factory management and control. However, the sage of big data, the way it is collected, processed and analyzed is still in its infancy, but provides great potential. Flexible small scale production systems with local production networks that are integrated on demand through cloud manufacturing can emphasize clean and competitive eco-factories. The emergence of impressive new business models have overwhelmed the IT industry in the last 15 years, and billion-dollar-heavy IPOs, and merger and acquisitions in the industry have pushed a rush for new innovative ideas and business models. The traditional manufacturing industry is taking advantage of these developments. A continuous cycle of design, production and sales incorporates standalone functions of the company as a competitive weapon. Collaborative product development based on crowd sourcing can realize projects or initiatives which are not limited by firm values. New business models like product-service-systems have already found their place in the manufacturing landscape, and will likely continue to grow. Especially SMEs are candidates to better adopt product-service-systems, since currently they are hold back due to organizational and implementation hurdles. These turbulent environment and changing paradigms put pressure to develop our factories out of the industrialization age into information and sustainability age.

5.3. Toward eco-factories

The focus group concentrated on providing answers to the question of what solutions should be considered in the next 20 years for eco-factories. The focus group discussion, including the brainstorming technique and affinity diagramming technique, led to the development of the framework for future eco-factories as highlighted in Fig. 3.

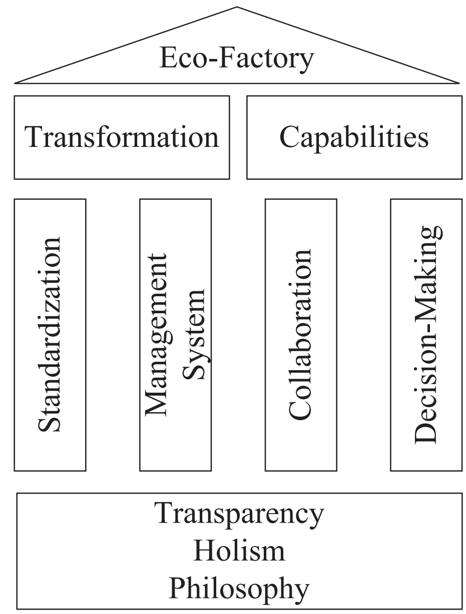


Fig. 3. Framework for future eco-factories.

5.3.1. Fundament: Transparency, holism, and philosophy

Transparency and sustainability initiatives have a reciprocal connection. On the one side transparency is key to any CSR reporting initiative, and on the other side company-wide reporting about sustainability initiatives is a lever to improve the internal and external transparency. Transparency mutually supports the understanding and comprehension among internal and external stakeholders, along with the issue of holism. Optimization and improvement tools for each of those subsystems are now commercially or scientifically available, however integrated perspectives which address internal and external variables are necessary and are significant levers for eco-factories. The holistic integration engineering disciplines like manufacturing and industrial engineering, energy engineering, and civil engineering as well as social sciences like human resource management and change management will likely be on top of the research agenda in the future. The third element that is absolutely necessary according to the expert group is philosophy. In order to create truly sustainable eco-factories, companies have to adapt a philosophy which matches its goals. This is not an overnight process, but takes several steps of innovation and corporate culture. It was compared to the emergence of the Toyota production system that evolved over several years in the last century. To reap the full benefits of sustainability, it is paramount that change and innovation is not solely introduced in the technical systems of the factory, as it currently happens. A philosophy encompasses the management and the employees, and provides a vision and guidance for the direction of the company. Moreover, the more the people in the company adopt this philosophy and commit to it, the better improvements the company can undergo with increased implementation success. Companies have to fully embrace the mind-set of eco-factories and this mind-set needs to be mentored and lived throughout the entire organization. These structures cannot just be emulated or simply adopted or governed by the utilization of some fancy three-letter-acronym, but they emerge as a consequence of a homogenous appreciation of transparency, holism and philosophy.

5.3.2. Levers: Standardization, management system, collaboration, decision-making

Standards and labels are very important for future eco-factories. Standards are a meaningful way to lower transaction costs and make processes transparent since they are organized around commonly accepted information which can be accessed by any organization. Using standards creates impacts on the risk management of technological advancements inside the company and supports the integration of solutions outside the company. Besides patents and licenses, standards foster the technological spillover and distribution of innovation, and foster the creation of a dynamic marketization of sustainable products and services. Standards and labeling activities which are directly concerned with the eco-design and eco-operation procedures like the ISO 14955 on energy consumption of machine tools are still in their infancy. Management systems have to be adapted accordingly. Rather than viewing sustainability as an add-on, it should serve as an umbrella unifying and positioning the management approach and tools. Conventional financial and managerial systems are not organized to embrace sustainability principles. The triple bottom line, a term coined in accounting, shows explicitly the need to enlarge the current management systems. For example, inventory or on-plant energy generators should not be treated as assets. Customized costing methods and management techniques are necessary to take the next step. Integration of sustainability is a complex and systemic task and efforts for firm's individual exploration and exploitation can and will fail. The interdisciplinary and complexity of the issue is difficult to grasp, and it requires cross-boundary expert knowledge and stakeholder integration to tackle challenges. A single organization cannot mobilize these amount and interdependencies of resources, knowledge, skills, competencies and capabilities to prolong successfully on its own. Rather than the individual's strength and power, the structure of the collective's interconnections determines successful approaches. Collaboration is the cornerstone to move away from traditional economic-set competition and cooperation environments to co-opetition. The creation of value has to be in the foreground in order to redeem long-term profits. Collaboration brings advantages like more efficient implementation, rapid resolution of problems, efficient usage of resources, mutual learning and improves relationships to customers. On the other side, it can always harbor risks due to conflicting goals and balances of power.

5.3.3. Enablers: Transformation and capabilities

Ambition and ambiguity are important relicts for eco-factories. It is ambitious, because it is clearly focused on the improvement of anthropogenic actions influencing other people and living beings today and tomorrow. The role of human reformation willingness is being contested, and its ambiguous foundation across the three pillars – economic, social, and environmental – is very remarking. These bounded conceptualization and perception of sustainability, enfolds the idiosyncratic foundations for eco-factories: transformation and capability.

To foster the role of eco-factories, various initiatives focusing on techno-centric solutions are propagated, which includes reduction of resource and energy efficiency, and minimization of environmental impacts. However, those approaches are limited in their success to persuade the factory into the eco-factory. So called soft issues, like values, policies and change management practices play an important role to foster the transition process to complete eco-factories. While up to date initiatives were enforced by upper management level, stemming often from the corporate social responsibility agenda from corporate strategy, the firm itself and the manufacturing system in particular were treated as a black box. In that vein, it is of utmost importance now to integrate cultures and intra-organizational differences with social and psychological factors into the focus. Transformation is important at this point, and has to be adequately addressed, managed and guided.

Managing the internal transformation process goes hand in hand with the development, maintenance and enlargement of capabilities which are aligned to value creation and environmental impact reduction. Proactivity in innovation and management is required to establish those capabilities required to cut off on inefficient processes and products. Firms require organizational capabilities, i.e. building and developing organizational practices to sustain business growth, as well as sustainable management capabilities, i.e. innovating and adapting in accordance with the sustainability paradigm and improving on financial and environmental performance. Capabilities are more than objectives and goals, or any practices or initiatives started in the company. It is the development and application of competencies with an expert manner to successfully transform those initiatives and practices according to the firm's goals and objectives in corporate strategic directions. Two critical aspects are presumed here: (i) insertion of new resources to modify organizational and environmental practices, and (ii) dynamic capabilities for changing existing practices. The central focus is on the resource information which is an important input to these two instances, as it enables firms to make appropriate decisions regarding their existing environmental practices.

6. Conclusion

In this paper, rather than simply discussing and building on current frames of sustainability principles, that seem to have slightly contributed to development of eco-efficient practices in the industry, we emphasize the need to challenge such frames beginning with a focus on how to increase insights for both the industry and academia to better operationalize the principles. The study could thus foster further research and development in the field of eco-factories that sparks the interest of both researchers and practitioners.

The research has several theoretical implications. First, it provides a valid call for increased research endeavors in the organizational and individual behavior of organizations regarding eco-factories. Second, it shows how the socio-technical system of an eco-factory is not only triggered through green innovations or efficiency improvements, but that also the people as single entities of the system and the people as collaborative entities are rich inhibitors of enabling capabilities. Third, the research provides an inter-disciplinary boundary where traditional engineering research that concerns optimization of manufacturing system and traditional managerial research that is focused on behavior of people in organizational and firm contexts converge.

An interesting aspect is that the scientific literature and scholars are keen to emphasize on the market-based necessities for eco-factories – increasing energy prices, resource scarcity, public pressure. Sustainability improvement opportunities and solutions provided within the current literature and company practices often focus solely on technology advancement. However, our discussion with experts from industry, academia, policy-makers and associations draw a different picture. The research has shown that the firm's internal structure, organization and resource base play a central role to implement and adopt sustainability principles in manufacturing systems, and to truly create competitive advantage based on sustainability. The main argument for eco-factories, the solutions to build clean and competitive eco-factories, and the way toward efficiency and success is an intrinsic one. The organizational and individual behavioral factors play an important role in reaching these objectives. It is up to the company itself to create the required structure and infrastructure for being able to convert green ideas into market success. These internal issues have not been extensively addressed on the research agenda so far. In this context, interdisciplinary research with social science and engineers stands out as an important future research direction.

The managerial implications are stringent: firms working on eco-factories should be careful not to underestimate the potential of collaboration in its diverse forms – internal and external, employee, supplier, customer, and stakeholder. The dialogue between different stakeholders also with diverging aims poses a challenge for future eco-factories. Comprehending these issues, acknowledging them early in the process and structuring and identifying solution patterns can support decision-makers in shifting the movement toward eco-factories in the right direction.

One further research area is to investigate the role and effects of different enablers on eco-efficient manufacturing to achieve an industrial shift toward clean and competitive eco-factories, utilizing again a focus group approach. Other attempts could focus on developing tools and methods to promote eco-efficient initiatives in business, wide and free dissemination and distribution of these methods and tools to several groups in the industry and academia, hence fostering follow up workshops and awareness briefings along with the eventual development of a forum to enable effective industry-academia networking to continue.

The research limitation could be considered as the number of focus group studies which could be increased for the future work, and also with the inclusion of different industrial sectors, so that different findings could be derived from a collection of insights based on several workshops with a larger set of industry groups.

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