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A system model for green manufacturing

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A B S T R A C T

Manufacturing systems evolution is afunction in multiple external and internal factors. With today's global awareness of environmental risks as well as the pressing needs to compete through efficiency, manufacturing systems are evolving into a new paradigm. This paper presents a system model for the new green manufacturing paradigm. The model captures various planning activities to migrate from a less green into a greener and more eco-efficient manufacturing. The various planning stages are accompanied by the required control metrics as well as various green tools in an open mixed architecture. The system model is demonstrated by an industrial case study. The proposed model is a comprehensive qualitative answer to the question of how to design and/or improve green manufacturing systems as well as a roadmap for future quantitative research to better evaluate this new paradigm.

1. Introduction

A manufacturing paradigm embraces a group of integrated strategies, principles and techniques that work together to achieve one of more objective. The term green manufacturing was coined to reflect the new manufacturing paradigm that employs various green strategies (objectives and principles) and techniques (technology and innovations) to become more eco-efficient. This includes creating products/systems that consumes less material and energy, substituting input materials (e.g. non-toxic for toxic, renewable for non-renewable), reducing unwanted outputs and converting outputs to inputs (recycling). Thus as much as the word "green" is used to reflect environmental friendly awareness and/or state, when it is added to manufacturing it is used to describe manufacturing approach that is aware of its production/product impact on the environment and resources and include such impact in its overall efficiency planning and control.

As in any of the previous manufacturing paradigms (e.g. mass production or lean manufacturing), this new green manufacturing paradigm is an outcome of market and technological drivers. Higher global awareness of environmental risks as a result of the new green movement is shaping new customer requirements in many places. In addition, the evolving green technology (that encompasses a continuously evolving group of methods and materials, from techniques for generating energy to non-toxic cleaning products) together with more eco-friendly product designs (which focus on reducing the environmental impact of manufactured products and facilitates recycling) is helping in realizing the green manufacturing objectives in real practice.

Although interest in green manufacturing is increasing more and more within the research and industrial communities, a clear description of what is meant by this term is becoming more essential. Much confusion arises from failing to describe the meaning, impact and implementation of green manufacturing at various level of manufacturing. In other words more work is required to differentiate between green manufacturing practices and principles on the operational level (machines, workers…etc), process level (planning, control…etc) and system level (design, strategies…etc). Furthermore the relation between sustainability and green manufacturing needs to be better explained to avoid mixing the two terms and at the same time drawing a clear relation between them.

This paper presents a system model for the new green manufacturing paradigm. The model captures various planning and control activities required to migrate from a less green into a greener and more eco-efficient manufacturing. The model is an attempt to better explain green manufacturing and at the same draw a qualitative roadmap for green manufacturing realization.

2. Green as a competing manufacturing strategy

Researchers and managers argue about the value of investing in green technology and green transformation. Hoffman (2000), states that environmental and green attempts in manufacturing should

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move from being an environmental management approach to an environmental strategy. This will create a win–win situation by which manufacturers can improve their environmental performance while achieving economic gains. In addition, the cleaner production program adopted by the united nation promotes that green manufacturing will lead to improved competitiveness, productivity and efficiency of enterprises (www.unep.org). Companies all over the globe are under pressure from stakeholders to be eco-efficient (Klebnikoff, 1996). Justification to invest and implement green manufacturing techniques (or the ROI as sometimes called) stems from three main aspects. These aspects are briefly discussed as follows:

2.1. *Green manufacturing and efficiency*

Time is money, energy is money and consumables are money. Making the same product using fewer resources and/or energy is a good strategy to make money. In other words, being efficient through preventing waste is both eco as well as money efficiency. Thus management should acknowledge that the cost of green manufacturing initiatives will be out paid by the money saved in a more efficient system which in turn will positively impact the ROI. In manufacturing there are a lot of wastes that can be eliminated in the process as well as the product. Green manufacturing strategy to reduce wastes is outlined in Fig. 1.

2.2. *Green manufacturing and market share*

With new customer demands and higher awareness (Willson, 2011 and Ackerman, 1997) together with tougher global competitiveness pressure, manufacturing enterprises need to review their manufacturing strategies. Green manufacturing should be viewed as an opportunity to expand the local and global market share in this dynamic environment. A deeper understanding of green manufacturing strategies and techniques will enable manufacturers to realize that unlike other competing manufacturing strategies (like cost and time), being green positively impact all other manufacturing competitive edges (as shown in Fig. 2). For example reducing material wastes and energy consumption will reduce production cost and improve production time. Going green in manufacturing will also improve the quality of the production process which will in turn impact product quality and also will be more appealing to the growing number of customers looking for green manufacturers and products.

2.3. *Green manufacturing and government support and regulations*

Pressure from governments to evolve into green manufacturing is increasing. Thinking globally by the year 2007, EU, Asia, US, South America, the whole world's governments and even the UN developed and activated many regulations, penalties, tax benefits or obligations to become greener or more eco-friendly at different manufacturing stages (Hong Kong green manufacturing alliance report 2008). Thus green manufacturing techniques are becoming more and more a mandate rather than being an option when manufacturers think globally.

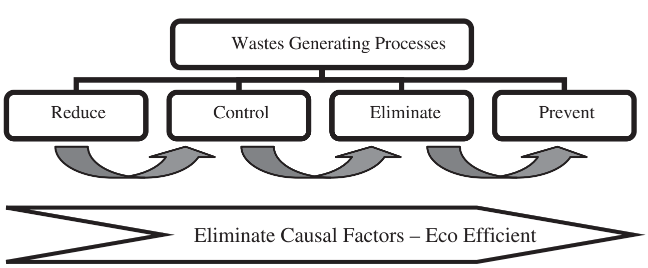

Fig. 1. Green manufacturing and wastes.

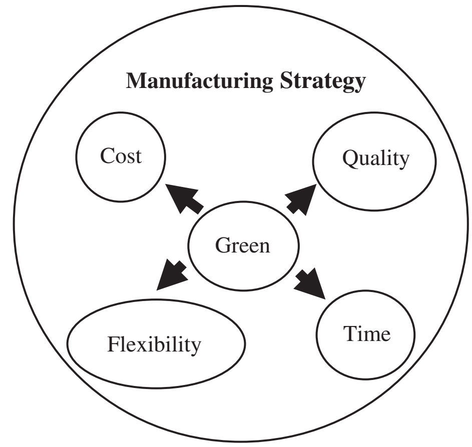

Fig. 2. Green manufacturing and competitive manufacturing strategies.

Based on the previous aspects, the transformation of current manufacturers into becoming greener can be economically justified. Integrating technological enablers with this economical understanding makes prospective green manufacturing a reality.

3. Green manufacturing and sustainability

The definition of sustainability which is generally adopted is: "meeting the needs of the present generation without compromising the ability of future generations to meet their own needs" (World Commission on the Environment and Development, 1987). With this definition all eco-friendly approaches, methodologies and research to preserve environmental conditions and resources through wastes reduction, prevention or recycling can be categorized under sustainability. Sustainability is a concept and a paradigm that has its different implementation and interpretation at different fields. For example, it is defined in the business field as "adopting business strategies and activities that meet the needs of the enterprise and its stakeholders today while protecting, sustaining and enhancing the human and natural resources that will be needed in the future" (Deloitte and Touche, 1992).

Green manufacturing deals with maintaining sustainability's environmental, economical and social objectives in the manufacturing domain. Reducing hazardous emissions, eliminating wasteful resources consumption and recycling are examples of sustainable green manufacturing activities. The author proposes the relation between sustainability as a concept and green manufacturing as a methodology in the following definition of green manufacturing: Green manufacturing is a sustainable approach to the design and engineering activities involved in product development and/or system operation to minimize environmental impact.

4. Review on green manufacturing

The available work on green manufacturing in its modern new context is considered to be few. The review can be divided into two groups, first, the work that dealt with the overall concept of green manufacturing and second, the work that provided various analytical tools and models to realize green manufacturing at different levels.

Examples of the first group is the work of Mohnty and Deshmukh (1998) highlighting the importance of green productivity as a competitive edge. They defined green productivity as all activities attempting to decrease wastes. They showed various case studies with different waste elimination practices to highlight the potential green productivity can have on the overall manufacturing performance. Naderi (1996) showed that green manufacturing is highly tied to waste management through the elimination of causal factors. Jovane et al. (2003) presented sustainable and green manufacturing as future paradigm with business model based on designing for environment using new nano/bio/material technologies. They highlighted that the new paradigm will respond to the customer need of more eco-friendly products. Wang and Lin (2007) proposed a broad triple bottom line framework to track and categorize sustainability information at the corporate level through a sustainability index system. The framework incorporated environmental and social costs and values into economic activities to support the decisions of the management. Their methodology was suggested to help decision makers to make green manufacturing plans. Burk and Goughran (2007) also presented another framework for sustainability to realize green manufacturing. The framework was based on their studies of SME manufacturers who achieved ISO 14001 certification.

Examples for the second group include the work of Melnyk et al. (2001) who proposed Green MRP tool. This tool is essentially a conventional Material Requirements Planning system that has been modified to include environmental considerations when converting the Master Production Schedule into the various component schedules. Through this inclusion, Green MRP solves the problem of minimizing environmental impact when managing industrial waste, by flagging potential component planning and environmentally related problems. Fiksel (1996) gathered different analytical tools that have emerged from product/process design research for green manufacturing. Examples of these tools include Life Cycle Analysis (LCA), Design for the Environment (DfE), screening methods and risk analysis. Hui et al. (2002) proposed a model to assess environmental hazards in manufacturing. In their model, the network analytic method was employed to analyze the potential of each impact category created by different kinds of waste in manufacturing processes. Additionally, fuzzy set theory was used to determine a numeric fuzzy weighting factor of each impact category contributing to the overall potential environmental impact on ecosystem. The model was limited to ecological health hazards. For realizing green manufacturing on the machine level, Krishnan et al. (2004) proposed environmental value systems analysis tool to evaluate the environmental performance of semiconductor processing. The tool develops environmental assessments through a “bottom-up” analysis approach, assembling equipment environmental models to describe a system. Cleanability and burr reduction which are another green manufacturing aspects also on the machine level were studied in various machine tool researches to act as another optimization objectives in their attempts to improve machine tool performance. Example of this type of work was presented by Avila et al. (2005) in the aerospace industry.

The above review is generally attempting to describe various aspects of green manufacturing as a concept and how to partially implement various technologies to improve green level. A required step to build on the overall available literature is having a holistic overall approach to realize green manufacturing. In other words, the literature of green manufacturing is missing a clear roadmap for manufacturing enterprises that can asses the current level of their greenness and offer a structured transformation plan towards becoming greener. This paper proposes a system model approach to fill this required gap. Compared to the existing models, the proposed model takes into account the various steps green transformation steps with the required planning objectives as well as the needed controllers and techniques in each of these steps.

5. System model for green manufacturing

The general purpose of developing systems models is to discover high-level frameworks for understanding certain kinds of systems, their subsystems, and their interactions with related systems. Thus, the purpose of the proposed green manufacturing system model is to better understand green manufacturing in terms of:

- Capturing the various activities required to asses the current green level of the manufacturing system
- Outlining the green transformation plan and the various tools and control metrics required in this transformation
- Describing how to sustain the achieved improvements and build on it to maintain more eco-efficient systems

Fig. 3 shows system model architecture for the design and control of the green manufacturing systems. The architecture is composed of two modules; the first module describes the design and planning processes of the green manufacturing systems and the second module describes the control process that controls the design and planning process at each level. The control module is based on performance measurements that reflect the strategic objectives and constraints indicated by the high-level decision makers at each level. The architecture as shown is open for that its information flow is accessible through any layer and it is mixed as it is composed of both hierarchal and partitioned levels. The architecture is made of four layers which will be discussed and explained in the following sections.

5.1. What is your color? (or performance assessment layer)

Any improvement process starts from assessing the current situation. The objective of this layer of the green manufacturing design and planning process is to identify how green the system is. The assessment process should be multidimensional where the

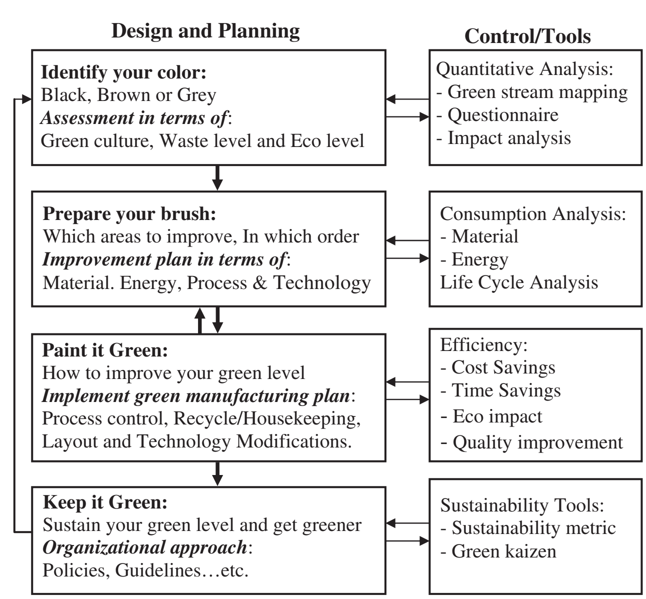

Fig. 3. System model for green manufacturing.

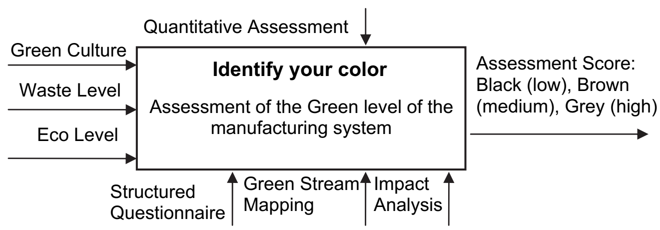

Fig. 4. IDEF$_0$ model for the assessment layer.

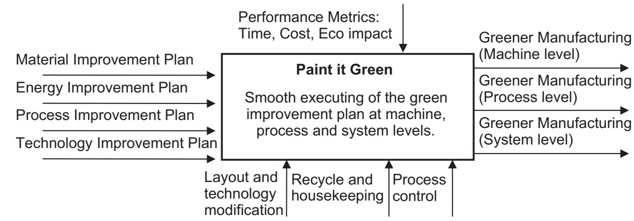

Fig. 6. IDEF$_0$ model for green manufacturing plan implementation layer.

level of greenness is measured across different manufacturing levels from operational level up to the system level. The challenge at this stage is to have a quantified assessment process. You cannot improve what you cannot measure. The quantitative assessment results (or assessment metric) will rank the manufacturing system with respect to green manufacturing benchmark targets or practices of the specified industry (in other words, what is their current color with respect to green). The assessment can rank non-green systems to be either close to green (so can have a grey color for example) or in the midway to being green (brown in color) or far from being green (black in color). These colors should have a respective quantitative value as will be explained. Furthermore, the assessment values will be used over the green transformation process as performance measure as well as improvement targets.

Green manufacturing metric (G2M) is a suggested metric under development by the author to fill the current need to have a comprehensive quantitative assessment measure. The metric will manipulate data gathered about the waste level (in terms of materials wasted/not recycled and energy consumed), eco level (in terms of environment impact/pollution and carbon print), and existing green culture in the manufacturing system (a qualitative measure of workers green practices and awareness activities) to act as inputs to a weighted mathematical formulation of the desired assessment. Various techniques can be used to gather input data including structured surveys, scorecards, impact analysis and green stream mapping (or GSM) which mimic the value stream mapping technique to capture green opportunities in the manufacturing system. Artificial intelligence techniques (such as fuzzy and agent systems) are investigated to be used to quantify both qualitative and quantitative measured data into the new metric. The metric values will reflect the green score with respect to each level in the manufacturing system. The assessment layer inputs, mechanisms, controls and output are explained using International Definition (IDEF$_0$) model shown in Fig. 4.

5.2. *Prepare your brush (or green manufacturing planning)*

In this layer, green improvement/implementation plan is generated in light of the previous assessment score. The planning phase is bounded by maintaining the required production level to meet market demand. This is particularly important to ensure manufacturers that green improvements or implementation will not negatively affect their productivity as traditionally assumed. The planning development should be carried out at the operational (machine) level, the process level and the system level with preset order dictated by the assessment score. The developed plan will include qualitative and quantitative action items with regard to material and energy type and consumption, process modifications and adjustments and finally technology implementation and improvement.

The generation of the plan at this stage is primarily and optimization process due to the nature of the objectives and various system constraints. The objective function will hold competing objectives like minimizing both energy consumption as well as material while maintaining a minimal cost. The constraints in this optimal plan will be achieving productivity that meets the demand, desired quality level as well as acceptable time. Various techniques should be explored to generate this plan like analytical hierarchical process (AHP), constraint satisfaction problem (CSP) techniques, theory of constraint, and various meta-heuristics techniques. The plan will be realized through translating optimal energy and material levels to layout modification requirements, optimal process parameters, optimal control parameters as previously mentioned. An IDEF$_0$ model for green improvement/implementation planning layer is shown in Fig. 5.

5.3. *Paint it green (or green manufacturing implementation)*

The next step after the development of the optimal plan is to gradually implement it. Each aspect of the plan (material, energy, process and technology) is decomposed and implemented either separately or concurrently with other aspects. A structured methodology should be developed for that implementation that maintains a balance between the current system configuration and practices and those of the optimal plan to ensure gradual transformation without affecting productivity.

Upon the implementation of the green manufacturing plan at each level, a reassessment process using the developed green manufacturing metric should be carried out. The reassessment

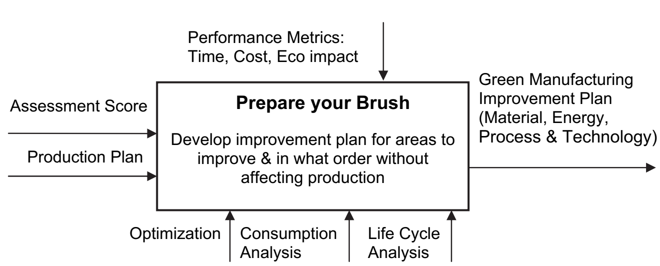

Fig. 5. IDEF$_0$ model for green improvement/implementation planning layer.

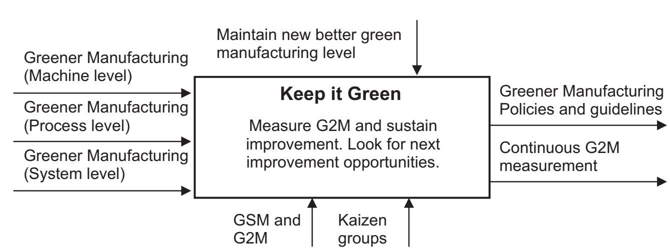

Fig. 7. IDEF$_0$ model for sustaining green manufacturing implementation layer.

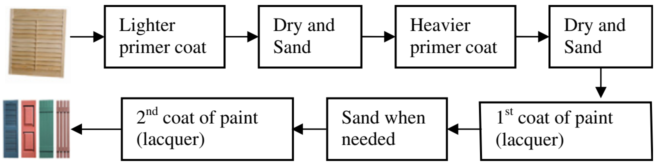

Fig. 8. Shutters paint line process.

process will measure the green improvement degree at various manufacturing levels achieved through the plan. Based on the assessment the plan will be judged as successful or not. An $IDEF_0$ model for green manufacturing plan implementation layer is shown in Fig. 6.

5.4. *Keep it green (or monitoring and sustainability)*

The real success of any improvement in manufacturing is measured by the degree of its sustainability. Green manufacturing realization should have sustainability as in an inherent component in any green planning activity. Green manufacturing policies and guidelines are one expected output at this stage. In addition, the continueous measurement of the greenness level at the various manufacturing levels together with green kaizen groups (or continuous improvement groups and initiatives) should be part of the normal planning and control activities in green faculties.

The problem at this stage of green transformation process is a typical dynamic control problem. The feedback of the continuous greenness measurement should trigger other green improvement plans and the process continuously goes on and on. An $IDEF_0$ model

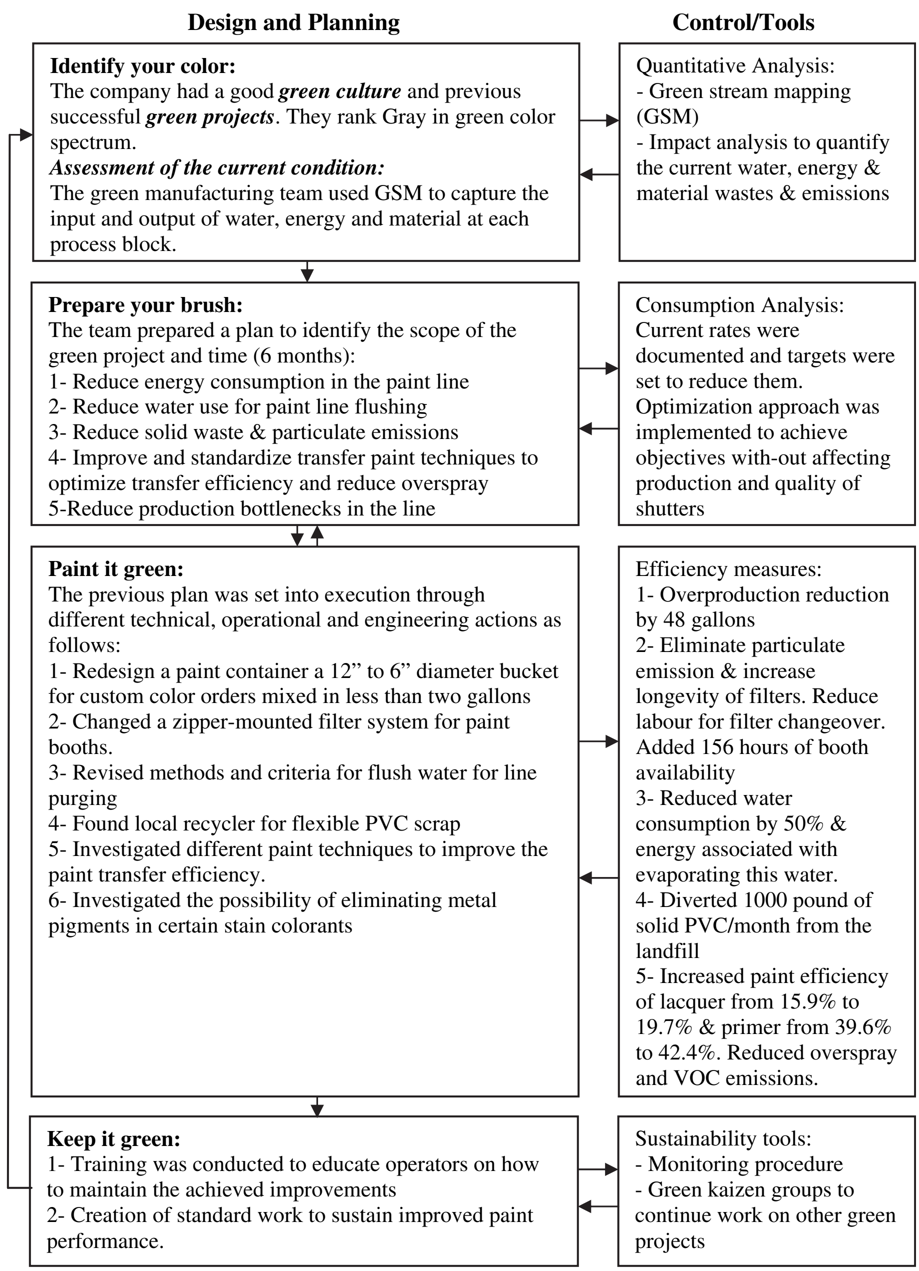

Fig. 9. System model for green manufacturing implementation in paint line.

for sustaining green manufacturing implementation layer is shown in Fig. 7.

6. Industrial case study

In this section, the proposed system model is illustrated by a successful application to an industrial case study. The case study involves different activities to improve the greenness level of a wood products manufacturer at its paint dept. The primary focus was the paint line of a specific product (shutters) which involved spray priming, sanding and spray printing. The process at that line can be summarized in the following steps: they apply a light primer coat, dry, sand, apply a heavier primer coat, dry, sand, apply a coat of paint (lacquer), sand where needed and finally, a second and final coat of lacquer (shown in Fig. 8).

Fig. 9 explains how the wood products manufacturing achieved a successful implementation of green manufacturing activities using the proposed system model. Table A1 in the appendix lists the annual cost, time, material and environmental savings for the implemented green manufacturing activities. Both Fig. 9 and table A1 demonstrate the feasibility and efficiency of the structure green manufacturing methodology offered by the proposed system model architecture.

7. Summary and future work

This paper presented a system model approach to realize green manufacturing. An open mixed architecture for the design, planning and control of green manufacturing activities was developed. The architecture describes the green manufacturing transformation process starting from determining the current green level of the manufacturing system (what is your color) to developing an optimal green plan (prepare your brush) to implementing the developed plan (paint it green) to finally sustaining the green improvements (keep it green). The system approach recognized that the green transformation is carried at different levels, mainly operational (machine), process and finally system level. The developed architecture also showed how each layer is controlled by different performance measurements that reflect the strategic objectives of the green manufacturing system. In addition, each of the mechanisms, tools and expected output of each layer were highlighted using international definition $IDEF_0$ models.

The proposed system model for green manufacturing was demonstrated through an industrial case study. The successful improvement of the greenness level of the paint dept. in the considered case highlighted the efficiency of the planning and control activities included in the presented system approach.

The architecture is considered a comprehensive explanation of the green manufacturing systems and opens the door for researchers to visualize the different areas that need to be developed in such systems. For example, various quantitative metrics together with various analytical techniques were suggested and recommended. This architecture is considered a novel architecture to tie different aspects of the design, planning and control of green manufacturing systems.

Future work is required to take the proposed qualitative system model into a quantitative level. Metrics like G2M, optimal green manufacturing plans algorithms, and structured green implementation methodology are examples of these quantitative requirements. Finally, industrial case studies are required to demonstrate the application of the proposed system model.

Appendix

Table A1 displays the cost savings of the industrial case study in their green manufacturing paint dept. project. The cost savings value can be increased by successful monetary quantification of some of the emissions and disposal reductions.

Table A1
Annual cost, time, material and environmental savings for implemented green manufacturing activities.

Reductions	Source of savings	Annual cost savings	Annual time, material & environmental savings
Labour/ Increased capacity	New filter system	$ 3800	Over 160 h
Material	Avoided paint purchase (raw material) due to new paint container design	$ 1440	48 gallons/year
	Improved transfer efficiency	$ 34,530	102 gallons primer 980 gallons of lacquer
Emissions	Improved transfer efficiency	Not quantified	968 pounds VOCs 82 pounds hazardous air pollutants (HAPS)
Disposal	Filters (longer life)	Not quantified	Not quantified
	PVC scrap to recycler	$ 670	6 tons scrap PVC
Water	New flush/purge water methods	$ 3000	1200 gallons/year
Energy	Reduced use of evaporators due to improved water use	$ 3000	120,000 kwh electricity
Total cost savings		$ 46,740	

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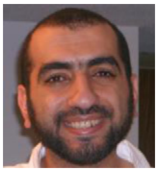

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