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Inverse Axiomatic Design: An Approach to Design Manufacturing Paradigms

Ãlaa Elsaied[a*], Hassan Soltan[b], Mohammed-Sobieh Hussein[c]

[a,b,c]*Department of Production Engineering and Mechanical Design, Faculty of Engineering, Mansoura University, Mansoura 35516, Egypt*

[a]*Email: a_elsaied@hotmail.com*

[b]*Email: hasoltan@hotmail.com*

[c]*Email: M.s.hussein@live.com*

Abstract

A robust manufacturing paradigm, as a part of manufacturing support system, pushes the manufacturing system towards worldwide manufacturing. That is achieved through the ability of waste removal and market responsiveness of a manufacturing system. Thus, several excellent manufacturing practices should be applied for that purpose. The selection and implementation of manufacturing practices isn't an easy task because of the cost and time consumed. Wrong practices lead to the failure of a manufacturing system. Therefore, this paper introduces a structured approach to design the manufacturing paradigm based on Axiomatic Design and Binary Ordering algorithm to minimize the running cost of manufacturing systems. The proposed approach is applied to a case from steel industry.

Keywords: Manufacturing paradigm; Axiomatic Design; Manufacturing practices; Binary Ordering algorithm.

1. Introduction

A manufacturing system consists of manufacturing facility and manufacturing support system [1]. The manufacturing paradigm is a part of the latter. Design of a manufacturing paradigm intends the selection and implementation of the most suitable manufacturing practices based on the principals of waste removal from the manufacturing process in addition to responsiveness to market demand in type and quantities.

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* Corresponding author.

However, the product design is the main determinant of the manufacturing system configuration. Wastes are classified into seven types by Toyota Production System as overproduction, defects, unnecessary inventory, inappropriate processing, excessive transportation, waiting and unnecessary motion [2]. Several practices, called lean practices [3-7], can be implemented to remove wastes from the manufacturing process such as

- TPM (total productive maintenance)
- 5S (sort, set, shine, standardize, sustain)
- Kaizen
- CMMS (computerized maintenance management system)
- FMEA (failure mode and effect analysis)
- PdM (product data management)
- SMED (single minute exchange of die)
- Poka-Yoke
- OEE (overall Equipment Effectiveness)
- Jidoka
- RCM (reliability centered maintenance)
- VSM (value stream mapping)
- Work standardization
- Takt time
- Job design
- Benchmarking
- Kansei engineering
- Production smoothing
- Kanban system
- QFD (quality function deployment)
- Aggregate planning

These lean practices represent a base for excellent manufacturing paradigms. They are often postulated as bundles. Each bundle of practices is characterized based on a class of waste, such as [3] who suggested four bundles—just-in-time, total quality management, total preventive maintenance, and human resource management. In [4], eight bundles of practices were postulated—human resource management, supportive systems, attitudes, product and process development, total quality management, basic strategies, preventive management, and manufacturing systems. The excellent manufacturing paradigm becomes a matter beyond the lean paradigm [4]. The approach of this paper is based on bundling of practices versus forms of wastes.

Remaining of this paper is organized as follows. Section 2 explores the Binary Ordering algorithm, as an aid segment of the proposed approach, that will be used for grouping (bundling) practices versus wastes. Section 3 introduces the proposed approach, Inverse Axiomatic Design, the main contribution of this paper. A case application is presented in section 4. Section 5 is concluding. Limitations of the proposed approach are found in section 6. Recommendations are reported in section 7.

2. Binary Ordering Algorithm

The Binary Ordering algorithm (BOA) is often used for categorical classification in different purposes such as *production flow analysis* in group technology [8] to form machine cells and part families in a logical way. Each machine cell is assigned to a family of parts so as to minimize the material flow between other cells. The BOA is employed, as in Figure 1, to accommodate our purpose—design of manufacturing paradigms, such that a manufacturing practice emulates a machine and a waste emulates a part, as if practices are machines remove wastes. The final output becomes bundles of practices versus families of wastes. Furthermore, as seen next, in the context of Axiomatic Design, functional requirements will play the role of waste removal requirements and design parameters will play the role of practices.

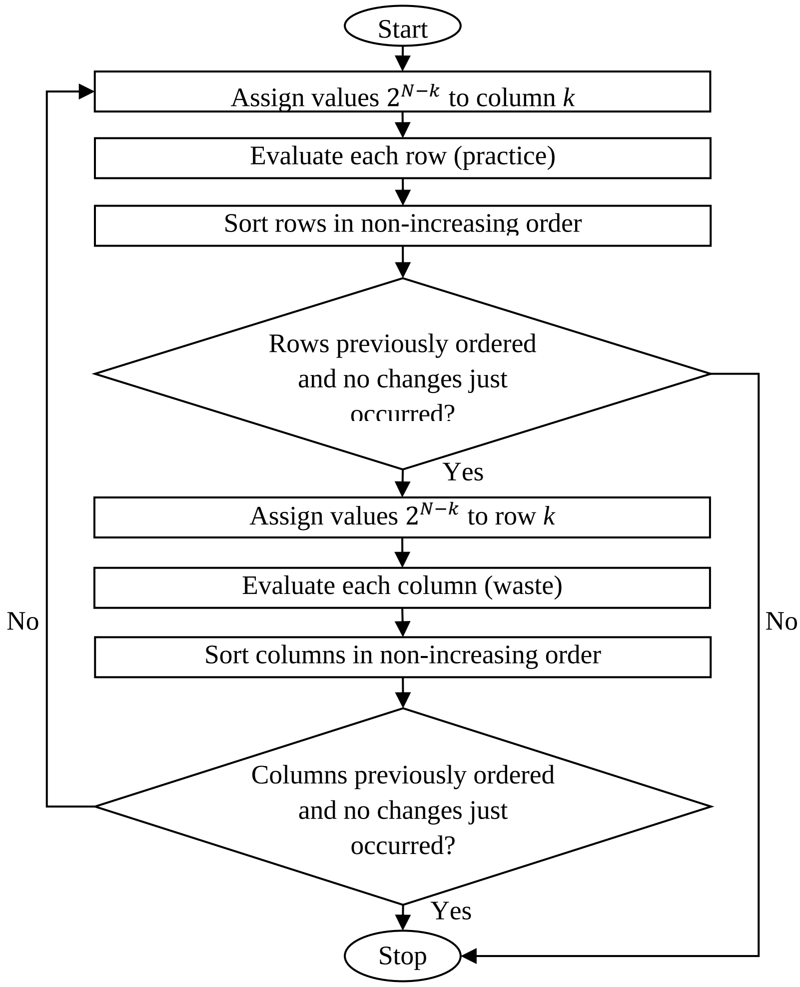

Figure 1: Binary Ordering algorithm [8].

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3. Inverse Axiomatic Design

Axiomatic Design (AD) is principally an approach used for product design. The AD divides the design process into four successive domains: *customer domain, functional domain, physical domain, and process domain*. The relationship between domains should be expressed as “Whats” and “Hows” according to the precedence relationship. Thus, the design process can be defined as mapping between the “What” and “How” domains. The process of mapping isn’t unique; the solution varies with a designer’s knowledge base and creative capacity. So, alternative design solutions can be obtained.

Once the customer attributes (*CAs*) are identified, they can be translated into functional requirements (*FRs*) in the functional domain. This translation must be done within a “solution-neutral environment.” This means that *FRs* must be defined without ever thinking about something that has already been designed or what the design solution should be. In order to satisfy these *FRs*, design parameters (*DPs*) are conceived in the physical domain. This mapping process between functional and physical domains is typically a one-to-many process; thus, for a given *FR*, there can be many possible *DPs* and vice versa. However, the *FRs* may subject to definition errors. Finally, the product is produced in terms of *DPs* through process variables (*PVs*) in the process domain. The mapping process is often expressed by the design equation,

$$[FRs] = [A][DPs] \tag{1}$$

where *A* is known as design matrix that relates *FRs* to *DPs* and characterizes the product design through some design axioms [9-11].

Goodness of the design solution can be evaluated by compliance with Suh’s two fundamental design axioms. Axiom-1, *independence axiom*: maintain the independence of the *FRs*; that reduces excessive interactions. Axiom-2, *information axiom*: minimize the information content of the design; that increases the probability of success of the product. To satisfy Axiom-1, *A* must be either diagonal or triangular. When *A* is diagonal, each of the *FRs* can be satisfied independently by means of its respective *DP*; such a design is uncoupled design. When *A* is triangular, the independence of *FRs* can be guaranteed if and only if the *DPs* are determined in a proper sequence; such a design is a decoupled design. Any other form of *A* is called a full matrix and results in a coupled design. The *FR*, *DP*, and *PV* can be decomposed into hierarchies. However, contrary to the conventional view of decomposition, they cannot be decomposed by remaining in one domain. One must zigzag between domains to decompose them. Axiom-2 provides a quantitative means of measuring the merits of a given design. Information is defined in terms of the *information content*, I, that is related in the simplest form to the probability, p, of satisfying the given set of *FRs* as

$$I = \log\frac{1}{p} = -\log p \tag{2}$$

The units of *I* depend on the base used for taking the logarithm. If log base two is used then the units are bits; if the natural log is used then the units are nats [12-14].

Inverse Axiomatic Design (IAD) is a different approach proposed here to design the manufacturing paradigm based on inversing the principal of decoupling in the original AD. In other words, Axiom-1 is inversely employed in order to maximize coupling between wastes and practices instead of its original purpose; that is called here as *inversed independence axiom* (Axiom-1^{inv}). Axiom-2 remains unchanged. It suggests grouping the most effective manufacturing practices such that each group focuses on eliminating some forms of waste. Such grouping selects the best practices to be applied in order to minimize the time and cost of paradigm implementation. Applying Axiom-1^{inv} makes those practices coupled to eliminate the most of wastes by the minimum number of practices.

The four domains of IAD are shown in Figure 2, the first domain "manufacturer domain" includes the main objective of the manufacturing system and the forms of waste that should be removes stated as it is, the second domain "waste removal domain" includes the forms of waste included in the system defined in terms of the seven wastes; e.g. mapping process is applied between customer domain and waste domain to translate the customer requirements into the seven well known forms of waste, the third domain "practices domain" is the domain including the manufacturing practices used to eliminate the forms of waste found in the system, the fourth domain "implementation domain" is the final domain where the manufacturing practices are implemented.

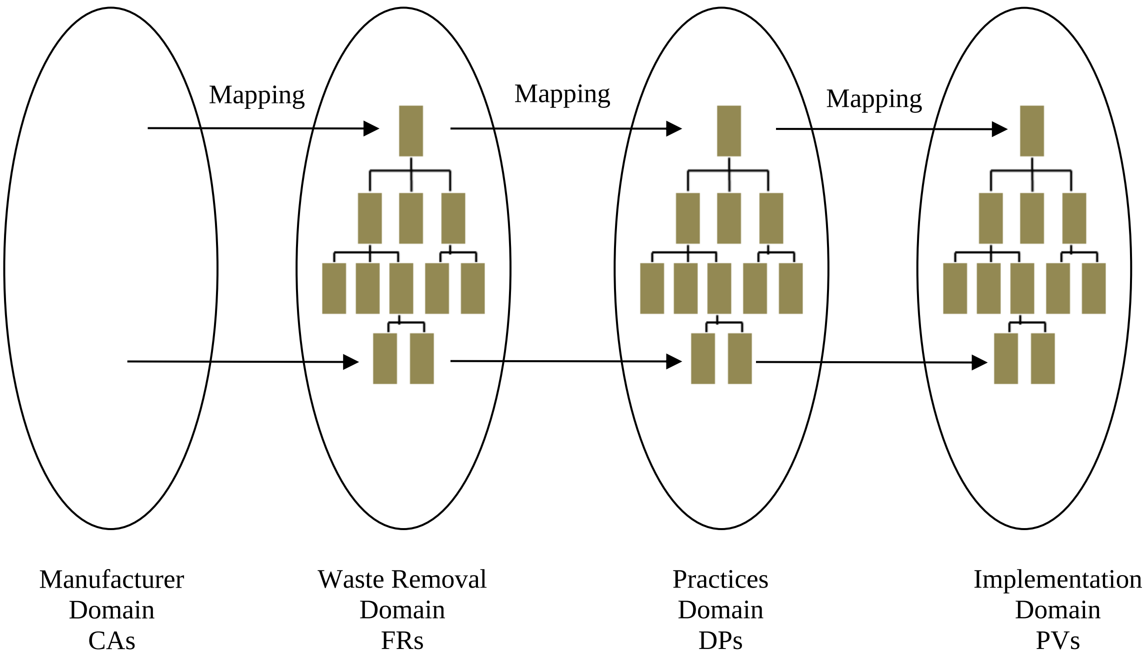


Figure 2: Domains of Inverse Axiomatic Design.

The forms of waste replaces the functional requirements and the manufacturing practices replaces the design parameters in the traditional AD mapping (Equation 1). Then, design matrix *A*, Table 1, modifies to represent the waste to practice relationship; that is *FRs* to *DPs* relationship. Here, *A* characterizes the manufacturing paradigm design through Axiom-1^{inv}. The values of x_{ij}'s of matrix *A* is either 1 or 0. If $x_{ij} = 1$, then practice *i* is associated with waste *j*; otherwise it isn't associated. The coupling value (degree of dependence) can be measured by the formula

$$D = \left(\frac{1}{n \times m}\right)\left(\sum_{j=1}^{m}\sum_{i=1}^{n} x_{ij}\right) \tag{3}$$

Where, *n* represents the number of practices and *m* represents the number of wastes. The value of *D* ranges from 0 to 1. If *D* = 1, it means full matrix; which means full dependency, and it is the most desirable case. If there are more than one set of practices have the same value of *D*, then Axiom-2 is applied guided by Equation 2.

The process of eliminating the whole forms of waste can be considered as a mapping process between "waste removal domain" and "practices domain." Also, here the mapping is one-to many process; thus, for a given *FR*, there can be many possible *DPs* and vice versa. The matrix *A* may be a square matrix or not; depends on the number of practices that can be implemented in the specified system. Once Axiom-1^{inv} is applied, Axiom-2 is applied to choose the best set of manufacturing practices. A framework for IAD is shown in Figure 3.

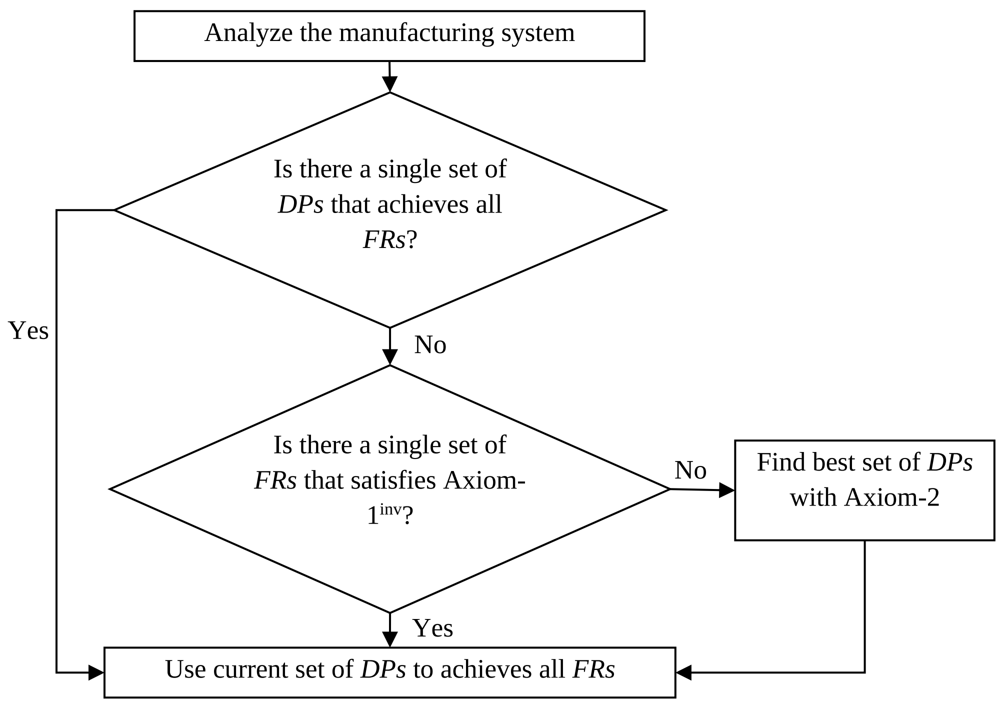


Figure 3: Inverse Axiomatic Design framework.

Refinement of current manufacturing practices is done first by grouping similar practices those focus on removing the same forms of waste and replace them with less number of practices that leads to less information content. The BOA is used here for this purpose.

Table 1: Paradigm design matrix *A*.

		Wastes				
		Waste-1	Waste-2	…	Waste-3	Waste-*m*
Practices	Practice-1	x_{11}	x_{12}	…	x_{13}	x_{1m}
	Practice-2	x_{21}	x_{22}	…	x_{23}	x_{2m}
	Practice-3	x_{31}	x_{32}	…	x_{33}	x_{3m}
	⋮	⋮	⋮	⋮	⋮	⋮
	Practice-*n*	x_{n1}	x_{n2}	x_{n4}	x_{n3}	x_{nm}

4. Application

ABC Company specializes in steel industry. ABC realized that unplanned manufacturing paradigm were the main cause of their failure, which eventually cost extra money and time. Their decisions for excellent practices implementation were based on the management experiences and subjective preferences. Planning with the approach proposed here, IAD approach, can reduce manufacturing wastes with a paradigm having minimum number of practices. Table 2 represents the relationship between the forms of waste found and the manufacturing practices that can be implemented [15].

A MATLAB software is developed to apply the BOA. Refer to Figures 4-6 and Tables 3 and 4. It appears that the forms of waste still grouped in eight families of waste, while manufacturing practices form groups, each of which focuses on removing some forms of waste. So, one or more practices are selected from each group and the others are discarded; therefore, the number of practices implemented is minimized as shown in Table 4. The primary and final degree of dependence are found D = 0.375 and D = 0.425, respectively. The degree of dependence is raised by 13.33%, while the cost of paradigm implementation is lowered, since a minimum number of practices are applied.

Finally, it can be said that the proposed approach, IAD, succeeds in minimizing the number of practices implemented while improving the dependency. The most efficient practices are selected, which improve also the efficiency of the system and reduces the overall cost of practice implementation and the cost of waste. Grouping of waste types helps also in clarifying the interrelationship between waste types and suggesting ranks for waste types from the one that has the maximum influence on the system performance to the minimum.

Table 2: A primary paradigm for ABC Company.

		Forms of Waste							
		Over production	Defects	Unnecessary Inventory	Inappropriate Processing	Excessive Transportation	Waiting	Unnecessary Motion	Non-Responsiveness
Manufacturing Practices	TPM		1		1		1		
	5S	1	1	1	1	1	1	1	
	Kaizen		1		1			1	
	CMMS		1				1		
	FMEA		1		1				
	PdM		1		1	1	1		1
	SMED						1	1	1
	Poka-Yoke		1		1				
	OEE		1				1		1
	Jidoka		1					1	
	RCM		1	1			1		
	VSM			1	1	1	1	1	1
	Work standardization				1			1	
	Takt time	1		1			1		
	Job design		1	1	1	1	1	1	
	Benchmarking		1		1				1
	Kansei engineering		1		1				1
	Production smoothing			1		1			
	Kanban system			1					
	QFD		1						
	Aggregate planning	1							

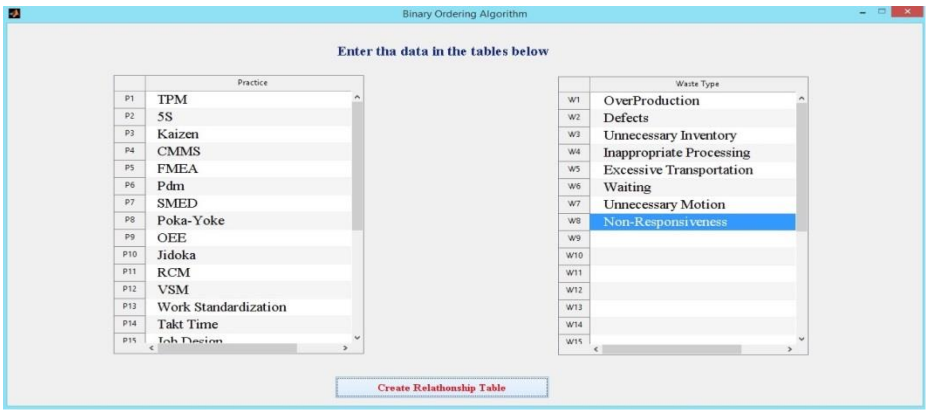
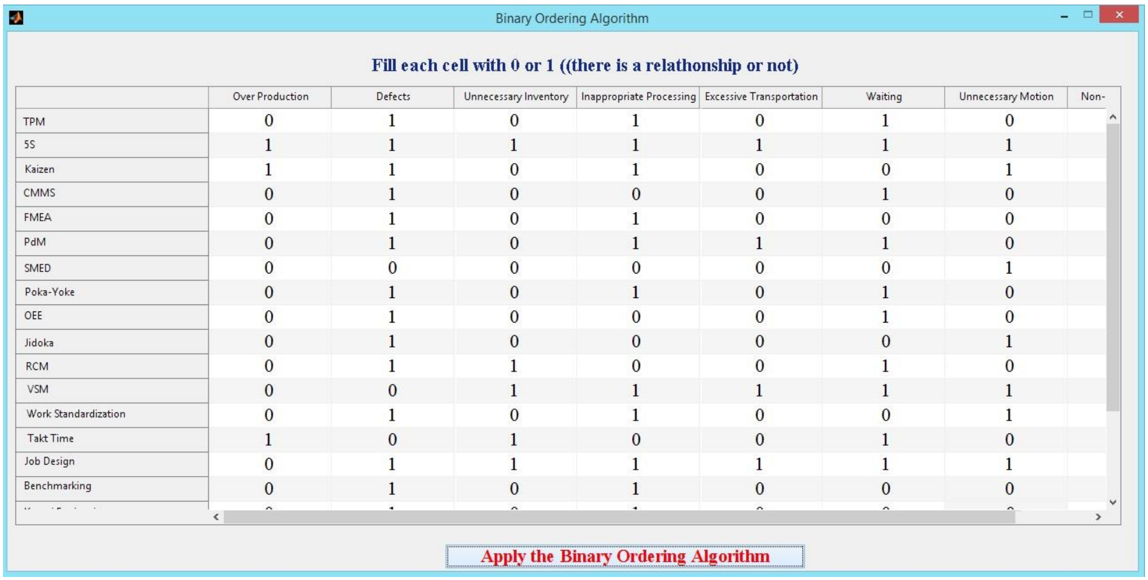
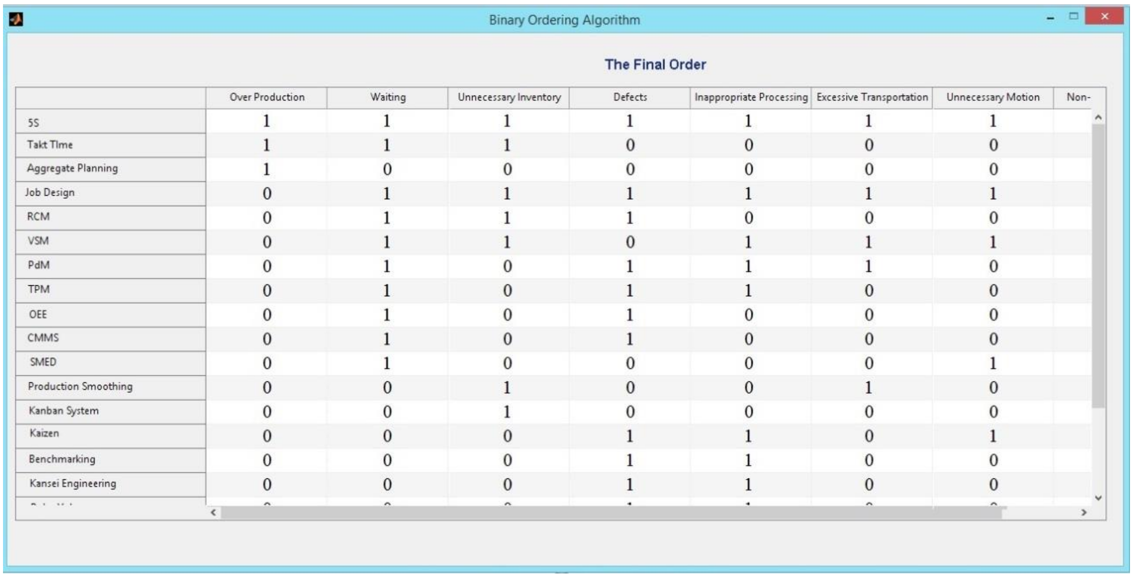


Figure 4: Input screen of practices and wastes.



	Over Production	Defects	Unnecessary Inventory	Inappropriate Processing	Excessive Transportation	Waiting	Unnecessary Motion	Non-
TPM	0	1	0	1	0	1	0	
5S	1	1	1	1	1	1	1	
Kaizen	1	1	0	1	0	0	1	
CMMS	0	1	0	0	0	1	0	
FMEA	0	1	0	1	0	0	0	
PdM	0	1	0	1	1	1	0	
SMED	0	0	0	0	0	0	1	
Poka-Yoke	0	1	0	1	0	1	0	
OEE	0	1	0	0	0	1	0	
Jidoka	0	1	0	0	0	0	1	
RCM	0	1	1	0	0	1	0	
VSM	0	0	1	1	1	1	1	
Work Standardization	0	1	0	1	0	0	1	
Takt Time	1	0	1	0	0	1	0	
Job Design	0	1	1	1	1	1	1	
Benchmarking	0	1	0	1	0	0	0	

Figure 5: Input screen of primary paradigm design matrix.



	Over Production	Waiting	Unnecessary Inventory	Defects	Inappropriate Processing	Excessive Transportation	Unnecessary Motion	Non-
5S	1	1	1	1	1	1	1	
Takt Time	1	1	1	0	0	0	0	
Aggregate Planning	1	0	0	0	0	0	0	
Job Design	0	1	1	1	1	1	1	
RCM	0	1	1	1	0	0	0	
VSM	0	1	1	0	1	1	1	
PdM	0	1	0	1	1	1	0	
TPM	0	1	0	1	1	0	0	
OEE	0	1	0	1	0	0	0	
CMMS	0	1	0	1	0	0	0	
SMED	0	1	0	0	0	0	1	
Production Smoothing	0	0	1	0	0	1	0	
Kanban System	0	0	1	0	0	0	0	
Kaizen	0	0	0	1	1	0	1	
Benchmarking	0	0	0	1	1	0	0	
Kansei Engineering	0	0	0	1	1	0	0	

Figure 6: Output screen (grouped paradigm).

Table 3: Grouped paradigm for ABC Company.

		Forms of Waste							
		Over production	Waiting	Unnecessary Inventory	Defects	Inappropriate Processing	Excessive Transportation	Unnecessary Motion	Non-Responsiveness
Manufacturing Practices	5S	1	1	1	1	1	1	1	
	Takt time	1	1	1					
	Aggregate planning	1							
	Job design		1	1	1	1	1	1	
	RCM		1	1	1				
	VSM		1	1		1	1	1	1
	PdM		1		1	1	1		1
	TPM		1		1	1			
	OEE		1		1				1
	CMMS		1		1				
	SMED		1					1	1
	Production smoothing			1			1		
	Kanban system			1					
	Kaizen				1	1		1	
	Benchmarking				1	1			1
	Kansei engineering				1	1			1
	Poka-Yoke				1	1			
	FMEA				1	1			
	Jidoka				1			1	
	QFD				1				
	Work standardization					1		1	

Table 4: A modified paradigm for ABC Company.

		Forms of Waste							
		Over production	Waiting	Unnecessary Inventory	Defects	Inappropriate Processing	Excessive Transportation	Unnecessary Motion	Non-Responsiveness
Manufacturing Practices	5S	1	1	1	1	1	1	1	
	Aggregate planning	1							
	Job design		1	1	1	1	1	1	
	VSM		1	1		1	1	1	1
	SMED		1					1	1
	Production smoothing			1			1		
	Kanban system			1					
	Kaizen				1	1		1	
	Kansei Engineering				1	1			1
	Jidoka				1			1	

5. Conclusion

Corrupted design of a manufacturing paradigm incurs high non-value adding costs to the manufacturing system. An approach, called *inverse axiomatic design*, to design right manufacturing paradigms is presented here based on the theory of Axiomatic Design. It suggests applying the Axiomatic Design *independence axiom* inversely to couple manufacturing practices and remove the forms of waste present in the system with minimum number of practices. A quantitative measure for the degree of dependence "*D*" is proposed to compare alternative solutions. Greater the value of *D*, the better paradigm design. BOA is used for grouping manufacturing practices to achieve higher dependency and less number of manufacturing practices by grouping similar practices and select the best amongst them. When alternative solutions have the same value of *D*, the *information axiom* is applied as in traditional Axiomatic Design to retain minimum information content.

6. Limitations

The proposed approach isn't limited to type or size of the manufacturing system. Nevertheless, the determination of wastes and assessment of their impacts on the manufacturing system needs to extensive analysis of value stream mapping. Also, the selection of candidate practices and their association with forms of waste is an exhaustive process. Unfortunately, there is no recorded standard values for the removal ability of practices versus wastes or cost values for implementation of practices. However, the successful application of the proposed approach needs to very specialized experts which may incurs extra costs.

7. Recommendations

It is recommended, in the design of a manufacturing paradigm, to adopt the sufficient practices that can remove the waste inherent to the manufacturing system with acceptable total system cost. In addition, it is necessary not to insert duplicated practices in the same group. Furthermore, all root wastes those found active in the system must be reordered and analyzed before the application of the proposed approach. This approach will be extended to comprise the impact of wastes on the manufacturing system in addition to implementation cost of practices.

List of Abbreviations

AD : Axiomatic Design
BOA : Binary Ordering algorithm
CAs : Customer Attributes
CMMS : Computerized maintenance management system
DPs : Design parameters
FMEA : Failure mode and effect analysis
FRs : Functional requirements
IAD : Inverse Axiomatic Design
OEE : Overall equipment effectiveness
PdM : Product data management
PVs : Process variables
QFD : Quality function deployment
RCM : Reliability centered maintenance
SMED : Single minute exchange of die
TPM : Total productive maintenance
VSM : Value stream mapping

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