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Classification scheme for lean manufacturing tools

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For the past few years almost every manufacturing industry has been trying to get 'lean'. A headlong rush to become lean also resulted in many misapplications of existing lean manufacturing tools often due to inadequate understanding of the purpose of tools. While tool descriptions abound, there is no way systematically to link a manufacturing organization to its problems and to the possible tools to eliminate these problems. The main purpose of this paper is to propose a classification scheme to serve as a link between manufacturing waste problems and lean manufacturing tools. A manufacturing organization can then match its manufacturing wastes with the appropriate lean manufacturing tools. The classification of existing knowledge is often the first step in moving from a practice to a science. This classification scheme systematically organizes lean manufacturing tools and metrics according to their level of abstraction, appropriate location of application of the tool in the organization, whether it addresses management waste or activity waste, the type of resource waste it addresses, and whether it identifies waste, measures waste, eliminates waste, or a combination of the three. We have organized 101 lean manufacturing tools and metrics using this classification scheme. We have also described some common manufacturing problems using this classification scheme and shown the problem–tool connection through examples. The classification scheme is not intended as a decision-making tool, i.e. it does not decide if something is a waste. However, the proposed scheme does an excellent job of classifying all well-known lean manufacturing tools and metrics and suggests lean manufacturing tools and metrics that will help to address manufacturing problems. This classification scheme will assist companies trying to become lean and can serve as a foundation for research into the science of lean.

1. Lean manufacturing

Lean manufacturing has been *the* buzzword in the area of manufacturing for the past few years. The concept originated in Japan after the Second World War when Japanese manufacturers realized they could not afford the massive investment required to build facilities similar to those in the USA. The Japanese, particularly Toyota, began the long process of developing and refining manufacturing processes to minimize waste in all aspects of operations (Thompson and Mintz 1999). Lean manufacturing, also known as the Toyota Production System (TPS), was originated by Taiichi Ohno and Shigeo Shingo at Toyota. It is now widely recognized that

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organizations that have mastered lean manufacturing methods have substantial cost and quality advantages over those still practising traditional mass production (Fleischer and Liker 1997).

The goal of lean manufacturing is to reduce the waste in human effort, inventory, time to market and manufacturing space to become highly responsive to customer demand while producing world-class quality products in the most efficient and economical manner (Todd 2000). Shigeo Shingo (1992) strongly advocated the elimination of waste and put forth the idea, 'don't accept waste as unavoidable'. The basis of lean manufacturing is the elimination of waste. Russell and Taylor (1999) define waste as 'anything other than the minimum amount of equipment, materials, parts, space, and time that are essential to add value to the product'. Waste takes many forms and can be found at any time and in any place. There is the waste of complexity, labour (the unnecessary movement of people), overproduction, space, energy, defects, materials, time and transport (Nicholas 1998, Boeing 2000). Waste uses resources but does not add value to the product (Search Manufacturing 2000). Lean manufacturing combines the best features of both mass production and craft production: the ability to reduce costs per unit and dramatically improve quality while at the same time providing an ever wider range of products and more challenging work (Womack *et al.* 1990).

The benefits of lean manufacturing are evident in factories across the world. Companies report improved product quality, reductions in cycle time, reduced work in progress (WIP), improved on-time deliveries, improved net income, decreased costs, improved utilization of labour, reduction in inventories, quicker return on inventory investment, higher levels of production, increased flexibility, improved space utilization, reduction in tool investment, a better utilization of machinery stronger job focus and better skills enhancement. The following overall performance gains have been attributed to the lean manufacturing concepts and tools (CITEC 2000, Connstep 2000, Zimmer 2000).

- Defects reduced by 20% per year, with zero defects performance possible.
- Delivery lead times reduced by more than 75%.
- On time delivery improved to more than 99%.
- Productivity (sales per employee) increases of 15–35% per year.
- Inventory reductions of more than 75%.
- Return on assets improvement of more than 100%.
- Improvements of 10% or more on direct labour utilization.
- Improvements of up to 50% in indirect labour utilization.
- 50% or greater increases in capacity in current facilities.
- 80% reduction in floor space.
- 50% improvement in quality.
- 95% machine availability.
- 80–90% reduction in changeovers.
- 60% reduction in cycle times.

Lean manufacturing uses tools such as *kaizen*, one-piece flow, cellular manufacturing, synchronous manufacturing, inventory management, *pokayoke*, standardized work, workplace organization and scrap reduction to reduce manufacturing waste (Russell and Taylor 1999). There exists a plethora of different tools and techniques developed for different purposes and waste elimination or reduction (Green and Dick 2001). Tools exist with multiple names, some of them overlap with other tools, and a particular tool might even have a different method of implementation proposed by different researchers. For example, value stream mapping is also referred to as process mapping. Hence, there is a need systematically to classify and organize these tools in a way that will make information about the tools readily available and will remove ambiguities in definition, purpose, and implementation of the tools. Applying the tools and metrics is difficult due to this confusion and the lack of a systematic classification of their applications (Gateway2Lean 2001). Misapplications of lean manufacturing tools and techniques have also been reported by companies in their pursuit to become lean (Factorylogic, discussion with senior consultants at the company, 2001). The misapplications are of three types: use of the wrong tool to solve a problem, use of a single tool to solve all of the problems and use of all tools (same set of tools) on each problem.

The misapplication of a lean manufacturing tool may result in the additional wastage of resources such as time and money. It may also result in reduced employee confidence in the lean philosophy. One such example is from a small manufacturer struggling with on-time deliveries due to a bottleneck in a manual operation. It implemented 5S, a tool it had been implementing all over the plant, thinking this would help solve their problems. They focused on taping, labelling, signs and other visual controls. Instead of gaining improvements, the cells became even more erratic in their cycle times, resulting in scepticism about lean in the company (Factorylogic, discussion with senior consultants at the company, 2001). The lean manufacturing classification scheme proposed in this research is intended to minimize the misapplication of tools and metrics.

2. Classification in manufacturing

With such convincing advantages to lean manufacturing, it is no wonder that an increasing number of companies are trying to become lean. However, becoming lean is not as easy as it seems. It requires total dedication from personnel, careful planning, strong leadership and adequate knowledge about the lean manufacturing philosophy, tools and techniques. A classification or systematic organization of lean manufacturing and lean manufacturing tools and techniques will be of great help for organizations becoming lean. In the past, classification schemes have been presented to classify manufacturing problems, manufacturing wastes and even lean manufacturing tools. Our work goes beyond these classification schemes but we took time to consider the functionality of these schemes. Therefore, we present a brief overview of these areas.

2.1. *Manufacturing problems*

There are many different types of manufacturing problems within each component of a manufacturing organization. Manufacturing problems can be of numerous types: personnel, quality, equipment, etc. Casti (1987) showed that each manufacturing problem exists at a certain hierarchical level (table 1), the lowest being raw materials, the highest being values. Further, he labelled each problem as a design, production or distribution problem. Finally, Casti showed that each problem has associated with it one or more characteristic, foundational system concepts, as he refers to them, that lend the problem its characteristic system flavour. These foundational system concepts are: flexibility/adaptability, complexity, efficiency/optimality, vulnerability/resilience, reliability, uncertainty/fuzziness, self-organization/replication and performance.

	Hierarchical level	Functional level	Conceptual level
IX	Values		
VIII	World industry		Efficiency
VII	Manufactured goods		Flexibility
VI	Industry	Design	Complexity
V	Local industry	Production	Vulnerability
IV	Finished product	Marketing	Reliability
III	Components		Uncertainty
II	Parts		Self organization
I	Materials		Performance

Table 1. Manufacturing system taxonomy (Casti 1987).

Putting the hierarchical, design–production–distribution and system concepts labels together supplies the basis for a classification scheme for manufacturing problems.

This classification encompasses a large scope. First, the entire world outside the plant is included. In addition, beyond production, design and marketing are included. Additionally, conceptual level concerns outside of the realm of waste are included. Of course, we intend to classify more than just a manufacturing organization. We must make sure, however, that our classification scheme allows for the inclusion of hierarchical levels I–V.

2.2. *Manufacturing waste*

Identifying and classifying manufacturing problems is of significant value to a manufacturing organization. True advances, however, come from exposing manufacturing wastes. Shingo and Ohno (Shingo 1992) identified seven different types of manufacturing wastes: overproduction, waiting time, transport, inventory, motion, defects and processing. Within the context of lean manufacturing, many researchers have extended the list of manufacturing wastes to encompass many other wastes mentioned previously (Womack *et al*. 1990, Liker 1998). Imai (1986) lists nine wastes in production: of rejects, in design, in WIP, in the first phase of production, in motion, in management, in manpower, in facilities and in expenses. Lists of wastes abound; classifications of wastes by where, when, how and why they occur do not yet exist. While exposing and classifying manufacturing, wastes can be the first step in improving a manufacturing organization. Identification is useless if the waste cannot be eliminated. It is therefore important to apply the correct tools, lean manufacturing tools, to eliminate manufacturing waste.

2.3. *Lean manufacturing tools*

Over the years, many lean manufacturing tools and techniques have been developed and every day new ones are proposed (Schonberger 1982, Dillon *et al*. 1985, Womack *et al*. 1990, Barker 1994, Liker *et al*. 1995, Cusumano and Nobeoka 1998, Liker 1998, Feld 2000, Taylor and Brunt 2001). With such a plethora of tools and techniques it is important and helpful to organize them into a systematic and logical manner. A systematic organization of these tools will help in their effective implementation of tools or for getting lean. For example, an organization or listing of tools according to the resource they are applied to will ease the process of tool selection for improvement. Taylor and Brunt (2001) developed a simple correlation matrix that relates seven different value stream mapping tools—process activity mapping, supply chain response matrix, production variety funnel, quality filter mapping, demand amplification mapping, decision point analysis, and physical structure volume and value—to the seven basic types of wastes identified by Ohno and Shingo. The correlation matrix is used to select the appropriate value stream mapping tools to eliminate a particular waste. Taylor and Brunt also identified a range of frequently encountered key processes in an organization; 12 value stream wastes within a component and assembly production, seven work environments, and wastes in warehousing. While understanding and classifying lean manufacturing tools is important, there is a need to consider the relationship of these tools and techniques to the manufacturing organization components, the problems they attempt to solve, the type of waste they address and the resources to which they are applied. The purpose of this paper is to propose a classification scheme that will enable matching lean manufacturing tools to the wastes they eliminate and to the manufacturing problems they solve. We believe this to be useful to both application and research. The lean manufacturing tools' classification scheme proposed by us would classify lean manufacturing tools and techniques by their relationship to the component of manufacturing organization where they are applied, the type of waste they identify, measure and eliminate, the resource they are applied to, and the characteristic of the resource they improve. This type of classification is useful to recommend the use and application of lean manufacturing tools for an organization trying to become lean.

3. Classification development

We propose a classification scheme for lean manufacturing tools based upon where and when the tools can be applied as well as the type of waste the tools seek to reduce or eliminate. The goal of this classification scheme is to classify a manufacturing organization into discrete, clearly defined elements that interact with each other to form a production network. The levelled representation will be used to classify every lean manufacturing tool or manufacturing waste problem as a function of the resources affected and characteristics of these resources. If both tools and problems can be classified with the same scheme, the correct tool–problem combination will be found more efficiently. It is important to understand that the scheme is the method by which all tools or problems are classified. The tools and problems themselves are not elements of the scheme, but they attach to the appropriate application level to complete their classification. The classification scheme is a tree structure and, hence, in the end, yields many possibilities that are derived by multiplying the elements at each level.

In this classification scheme, we have considered only the tighter definition of a manufacturing organization as our system. By manufacturing organization, we mean only those elements directly involved in producing finished goods by use of various resources like personnel, machinery, etc. It includes various production operations and processes, gauging and inspection operations, assembly operations used during the production of goods, maintenance, and resources used for stacking and transport. We have not taken into account other supplementary organizational departments like tool design, research and development, various material testing laboratories, janitorial, etc., since the purpose is to classify lean manufacturing tools and applications. The same principles can be very easily expanded to encompass the various organizational issues that have been excluded here.

To develop this classification scheme, we proceeded by developing the overall classification structure, each time improving upon the previous version. We then worked to define the specifics of each piece of this classification scheme. When defining the scheme we were looking to span the system as well as to create a set of elements that were orthogonal at each level of the classification. Lastly, we worked on the links between the structural elements. A logical linking between various levels of the classification scheme is important because it enables accurate and precise representation and classification of lean manufacturing tools. All along, we paid particular attention to the semantics of the classification scheme elements. We continually used real lean manufacturing tools and applications to verify the classification scheme. Reader should keep in mind that the intent is to classify lean manufacturing tools as well as metrics and manufacturing waste problems.

3.1. *Overall structure*

The overall structure of the classification scheme defines the levels or categories of elements that will later be broken down and linked. The classification scheme (table 2) consists of seven levels: system, object, operation, activity, resource, characteristic and application. The elements in this classification scheme are somewhat obvious, especially once they are filled out below. Any lean manufacturing tool or manufacturing problem can be represented by this scheme. This classification scheme not only relates the lean manufacturing tools to the waste they eliminate, the location where they are applied and the object to which they are applied, but also it specifically relates the tools to the qualities of resources that the tool improves and the operation in manufacturing during which the tool is applied. Utilization of this classification structure for tool–problem matching should be efficient. The elements into which each level of the overall structure is broken down are discussed below. The final classification scheme is shown in figure 1.

3.2. *System level*

Any manufacturing organization will consist of various levels of abstraction. Waste occurs at these different levels and various manufacturing operations and processes are carried out at these different levels to transform raw material into finished goods. Thus, any manufacturing facility will consists of a station where a job is performed, a cell, which is a collection of different stations, a manufacturing line, which will consist of a number of cells, a plant that consists of different lines for different products, and, in the end, a company as a whole that consists of various

Level	Definition
System	Organizational element under consideration
Object	Product state under consideration
Operation	Production task under consideration
Activity	Nature of the task under consideration
Resource	Elements consumed during the operations under consideration
Characteristic	Qualities of the resources under consideration
Application	Focus of the tool under consideration, i.e. if the tool identifies waste, measures waste, eliminates waste, or a combination of these

Table 2. Levels in the classification scheme.

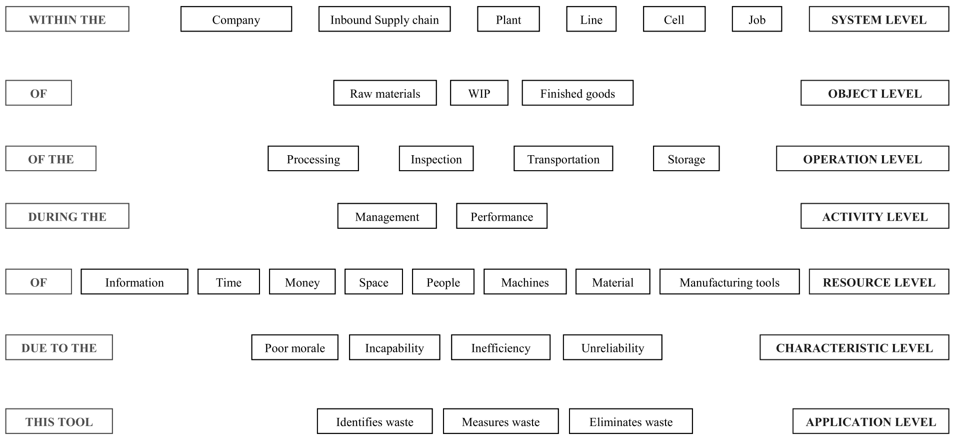

Figure 1. Classification scheme for lean manufacturing tools.

plants. For any company there is also an in-bound supply chain that supplies raw material to every plant or line or cell or station in the manufacturing facility. All these organizational elements constitute the system level in the classification scheme. These elements have been arranged in order of decreasing abstraction. A cell will consist of a group of jobs, a line will consist of a group of cells, a plant will consist of a group of lines and a company will consist of a group of plants. The in-bound supply chain is considered as a separate entity. Definitions of the elements that constitute this level follow. It is important to note the definition chosen here for a supply chain may be non-standard in the organizational sense but it fits our production focus.

- Company: organization that oversees a possibly diverse group of plants. The company level is concerned only with 'high-level' issues during manufacturing. At the company level there is no participation in the 'activity' of manufacturing.
- In-bound supply chain: encompasses the network and organizations involved in the movement of raw materials to the loading docks of the plant. The movement of material within a plant is not considered as the part of the in-bound supply chain. There is no WIP or finished goods involved in the in-bound supply chain. Wastes due to vendors' resources are not part of the scope of this classification scheme.
- Plant: group of possibly diverse lines at one physical site. All the goods moving in and out of the plant are considered at this level. The movement of raw material within the lines, cells and jobs will also be considered at this level.
- Line: group of cells and jobs producing one product or a family of products.
- Cell: group of stations with several jobs and work passing between them. Raw materials can be delivered directly to cells and cells can produce finished goods.
- Job: set of operations done at a station. Raw materials can be delivered to the job, but jobs do not produce or deliver finished goods. There is no management of any resource involved at the job level and there is no transport or storage.

It is understood that different organizations may use different terms for some of these organizational levels. Additionally, some organizations may have terms for intermediate levels, especially between plant and job. These intermediate levels could still be included in this scheme.

3.3. *Object level*

After the system level, the next classification is based on the material flowing through the organization. A manufacturing facility transforms any kind of raw material into a finished product. The finished product may in turn be a raw material to another facility. Any manufacturing activity can be thought of as carried out on one of the three objects—raw materials, WIP or finished goods—and these activities can be carried out at each of the system level elements. These elements are arranged chronologically.

- Raw materials: objects on which operations in the plant have not yet begun.
- WIP: any material on which operations in the plant have already begun but are not yet completed.
- Finished goods: objects on which operations in the plant have been completed.

3.4. *Operation level*

At any given instant, within any given system and on any given object there are only four operations done to move objects closer towards being a finished product: processing, inspection, transport or storage. It is possible that an organization may wish to have a finer delineation of operations, but that would make the scheme system specific. The operations are arranged somewhat chronologically.

- Processing: any operation or series of operations done on an object that changes its geometry or physical properties.
- Inspection: examination and evaluation of the physical attributes of an object (defined at the object level) or resource (defined at the resource level).
- Transport: any movement or conveyance of any object.
- Storage: temporary holding of an object.

3.5. *Activity level*

Any given operational element consists of two general activities: the management and the performance of that operation. The two activities are quite different and therefore so are their wastes and tools.

- Management: organizing and allocating of resources for operations.
- Performance: undertaking of operations on an object.

3.6. *Resource level*

During any operation, during either its management or performance, resources will be consumed and perhaps wasted. For any manufacturing operation to be performed there are eight resources: information, time, money, space, people, machines, materials and manufacturing tools. Again, a finer delineation may be possible, i.e. salaried time and hourly time, but these would be specific to the system. There is no logical order to the resources.

- Information: any data or knowledge acquired or supplied that aids in or is necessary for an activity.
- Time: any part of the period before an object reaches the market.
- Money: finances used to support the system and its activities.

- Space: area available in the system for operations.
- People: all employees working in the system to accomplish the operations.
- Machines: physical devices that accomplish operations in the system.
- Materials: compose the objects undergoing operations.
- Manufacturing tools: various tools used to facilitate the management and performance of manufacturing. For example, software used for planning, MRP, process charts, etc. Manufacturing tools are not lean manufacturing tools. Manufacturing tools are also not machine tools. Lean manufacturing tools eliminate or measure waste in the manufacturing tools.

3.7. *Characteristic level*

For measuring and evaluating the performance of a system with respect to the resources, different performance parameters or performance characteristics are used. For any given resource, the performance of the resource can be evaluated using four parameters, either independently or in combination: poor morale, incapability, inefficiency and unreliability. These may be thought of as the ways in which the resources can be wasted. Note that poor morale applies only to people at the resource level, and for the resources time, money and space only the characteristic inefficiency applies. These characteristics are related to the various resources consumed during manufacturing. For example, one can say incapability of machines, or inefficiency of machines or unreliability of machines. There is no logical order to the characteristics.

- Poor morale: unwillingness of people to excel at activities in the system.
- Incapability: inability of a resource to perform the assigned activity.
- Inefficiency: failure to perform the assigned activity with the least use of resources.
- Unreliability: inconsistency of quality of the resource.

There are a number of other characteristics commonly used in manufacturing lingo related to various resources. The characteristics described above can be used in combination to represent all other characteristics commonly used in the manufacturing organization. For example, inflexibility of personnel can be thought of as a combination of incapability, inefficiency and unreliability. Inflexibility of an assembly line is again a combination of incapability, inefficiency and unreliability. A lack of repeatability of a machine can be represented using a combination of inefficiency and unreliability, etc. The variance in terms used is too great to list all possibilities and still maintain orthogonality.

3.8. *Application level*

Every lean manufacturing tool can be classified as identifying waste, measuring waste, eliminating waste or a combination of these three. These applications are defined as follows.

- Identifies waste: picking out of which is resource used and possibly how much of it is waste.
- Measures waste: quantification of waste or any non-value added activity.
- Eliminates waste: eradication or reduction of waste or any non-value added activity.

3.9. *Classification linkages*

The seven levels and the elements in these seven levels as discussed above form a complete classification scheme for lean manufacturing tools, metrics and manufacturing waste problems. The last step is to arrange and link these different levels logically so that they can be effectively used to classify or represent any lean manufacturing tool or metric and its application. We arranged these seven levels in a top-down logical order based on level of abstraction and link each element in these levels. Lastly, we created a 'story' to explain the linkages using the words in the boxes to the left. Such linking enables users to represent every lean manufacturing tool, metric or manufacturing waste problem in a uniform and consistent manner. This avoids confusion and aids the better understanding of tools. Note that some of the linkages in the classification never make sense. For example, poor morale of information, time, money, space, machines, material or manufacturing tools never makes sense. Similarly, storage of objects at the job level, or performance of activities at the company level or management of activities at the job level does not make sense.

Figure 1 shows the complete structure and all elements of the classification scheme. The boxes on the right with all capital letters represent the names of the different levels of the classification scheme as described in the overall structure. In the middle are the elements of each level. The boxes on the left with all capital letters are used to string together a meaningful 'story' for each particular chain of boxes from bottom to top to represent a particular tool, its application or a problem. For example, one could say this tool *measures waste* due to the *inefficiency* of *people* during the *management* of the *inspection* of *WIP* within the *plant*. Our ability to create a logical 'story' guided us in the linking of the classification levels. This is explained in more detail below.

This classification scheme defines the areas of waste during manufacturing. This scheme will be used to classify lean manufacturing tools and metrics, and manufacturing waste problems into proper cubby-holes. The cubby-holes are placeholders in the classification scheme that 'hold' the tools. A tool's cubby-hole falls at the bottom of the classification scheme where a specific string of elements ends. With elements at each of the seven levels, there are actually 13 824 possible cubby-holes. Discounting for the non-feasible links in the classification scheme, we have 9888 feasible cubby-holes in the classification scheme. Tools, metrics or problems can have more than one cubby-hole (i.e. it is widely applicable) and there can be cubby-holes with multiple tools, metrics or problems (i.e. several tools can solve this problem) or no tools, metrics or problems (i.e. there are no existing tools to address this type of waste).

4. Verification

After proposing the structure, details and linkages for the classification scheme, we proceeded to verification. We first classified 101 lean manufacturing tools gathered from the lean manufacturing literature. The list of lean manufacturing tools has been compiled from various published and unpublished works. Our goal was not a complete list of lean manufacturing tools but a verified classification scheme. Owing to space constraints, we show here five representative tools and the accuracy of their classification. The definitions of these five tools—cellular layout, facility layout diagrams, load levelling, six sigma and value stream mapping—are shown in table 3. These five tools were chosen to show a variety of classifications. Note that although classification of only five tools has been represented here, we have classified all 101 compiled lean manufacturing tools using this classification scheme in a similar

Tool	Definition
Cellular layout	The arrangement of machines in small cells mostly in a U or O shape.
Facility layout diagrams	Visual diagrams to represent position of machines on the manufacturing facility.
Load leveling	Assigning of work to all machines, cells, or lines to match the outputs to reduce idle time.
Six sigma	A philosophy of improving quality by reducing defects.
Value stream mapping	A graphical tool used to map the as-is situation of the organization, to identify opportunities for waste elimination, and to decide the improvements to be implemented to eliminate the waste.

Table 3.

manner. During the tool classification process, we have only considered the direct effects of waste reduction by the use of the tool. We have not considered any indirect effects due to the use of the tool. For example, the use of 'employee recognition' has a direct effect of improving employee morale and an indirect effect of reducing product defects. This tool would thus be considered to reduce waste due to poor morale and not due to poor efficiency.

Verification entailed classifying the lean manufacturing tools using the scheme and confirming there were no problems with the structure or definitions of elements, nor conflicts between the existing definition of the tools and the definition of the tools as given by the classification scheme. We have not yet validated the scheme in a manufacturing environment to prove that the manufacturing problems can be classified and correct tools and metrics be applied efficiently using this classification scheme. Although not detailed here, we also verified the classification scheme by classifying directly and indirectly dozens of manufacturing waste problems found in the literature and through the authors' experiences as a lean manufacturing evaluator. The results were identical to those from the classification of the tools and metrics.

There were some problems encountered in classifying these five tools. They were normally due to the inability of the four words used at the characteristic level to represent the manufacturing jargon used for characteristics of various resources. Even though all such words can be effectively represented by the combinations of the four words used at the characteristic level, the severity of this problem in classification largely depends on user perception and the ability of the user to represent words. Similar problems were encountered while classification of other 96 tools.

- Cellular layout: classified by the classification scheme as shown in figure 2. The shaded boxes denote the classification of the tool. The shaded boxes at the system level represent various systems at which the cellular layout can be applied. Similarly, the shaded boxes at the subsequent levels represent the elements where a cellular layout can be applied to eliminate waste. Using the boxes on the left and the shaded elements of the classification scheme, we can classify cellular layout by the following 'story'. Cellular layout: this tool eliminates waste due to the incapability and inefficiency of information (for incapability and inefficiency), time (only for inefficiency), money (only for inefficiency), space (for incapability and inefficiency), people (for incapability and inefficiency),

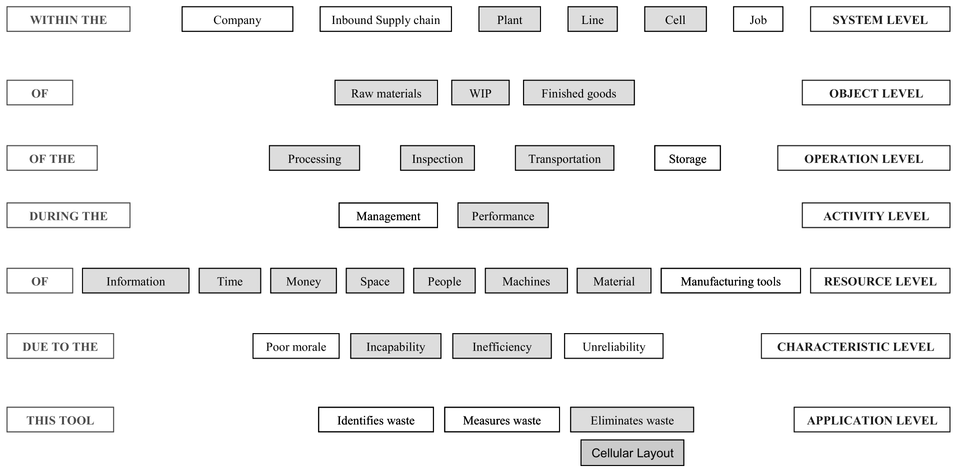

Figure 2. Classification of cellular layout using the classification scheme.

machines (for incapability and inefficiency) and material (for incapability and inefficiency) during the performance of the processing, inspection, and transport of raw materials, WIP and finished goods within the plant, line and cell.

- Facility layout diagrams: similarly classified (figure 3). This tool identifies and measures waste due to the inefficiency of space and machines during the management and performance of the processing, inspection, transport, and storage of raw materials, WIP, and finished goods within the plant, line and cell.
- Load levelling (figure 4): eliminates waste due to the inefficiency of time, people and machines during the management and performance of the processing, inspection, transport, and storage of raw materials, WIP, and finished goods within the plant, line, cell and job.
- Six sigma (figure 5): measures waste due to the incapability and inefficiency of machines and material during the performance of the processing and

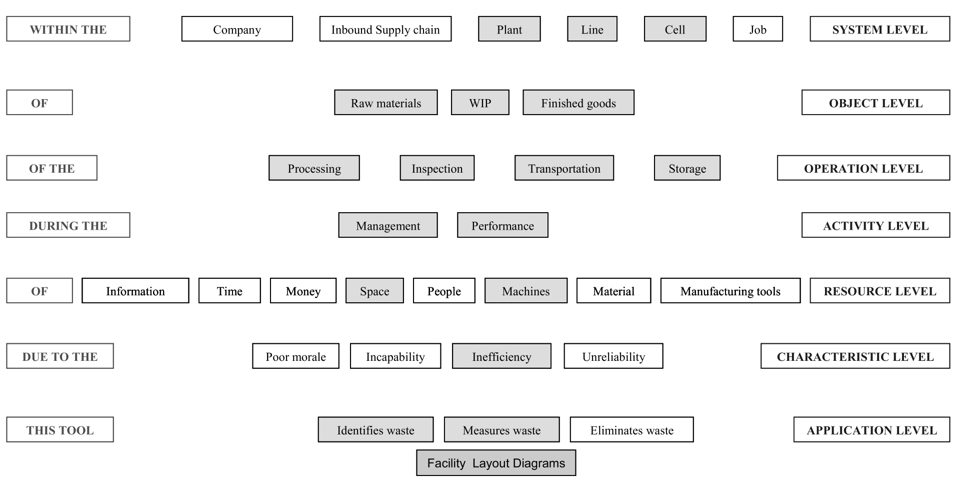

Figure 3. Classification of facility layout diagrams using the classification scheme.

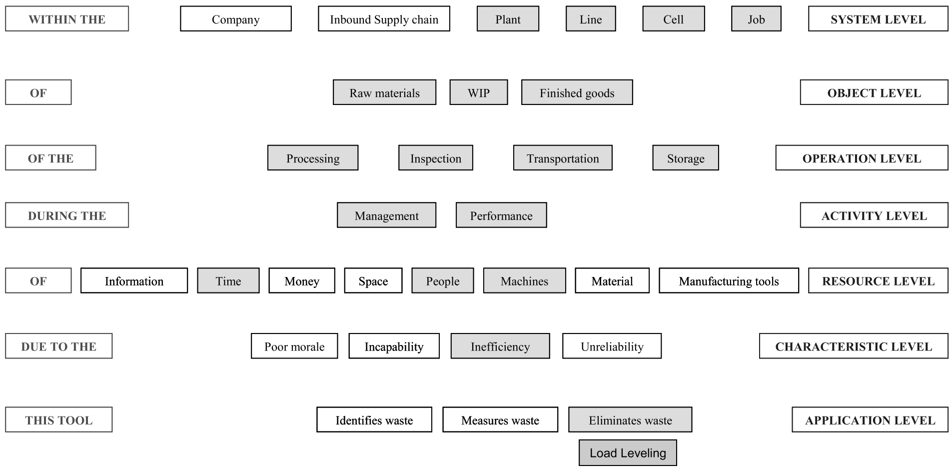

Figure 4. Classification of load levelling using the classification scheme.

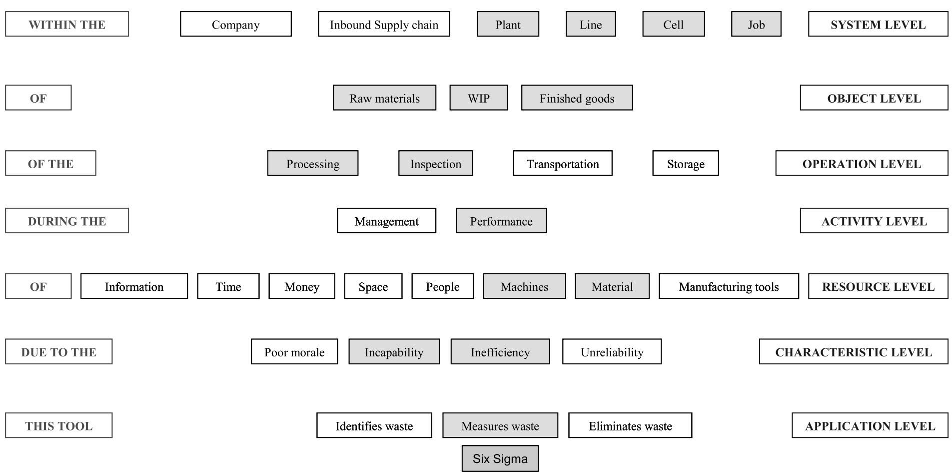

Figure 5. Classification of six sigma using the classification scheme.

inspection of raw materials, WIP, and finished goods within the plant, line, cell and job.

- Value stream mapping (figure 6): identifies waste and measures waste due to the incapability, inefficiency and unreliability of information (only for inefficiency and unreliability), time (only for inefficiency), money (only for inefficiency), space (only for incapability and inefficiency), people (for incapability, inefficiency, and unreliability), machines (for incapability, inefficiency and unreliability), material (for incapability, inefficiency and unreliability) and manufacturing tools (for incapability, inefficiency and unreliability) during the management and performance of the processing, inspection, transport, and storage of raw materials, WIP, and finished goods within the company, supply chain, plant, line, cell and job.

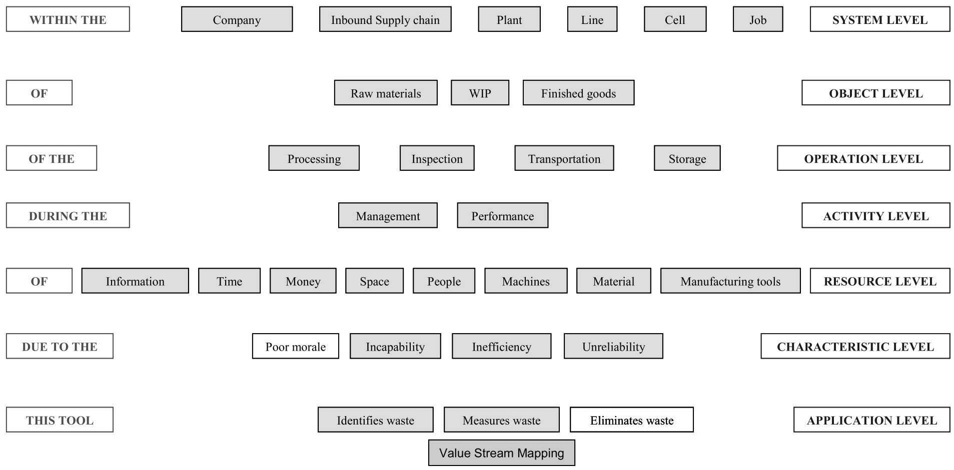

Figure 6. Classification of value stream mapping using the classification scheme.

One thing we learned while using this classification scheme is that the end user must clearly understand the scope and definitions of each element of this scheme before beginning. Not all definitions are intuitive. This could be corrected. However, no matter the changes in semantics, there would always be some learning necessary. In classifying all of the tools and metrics, we have not encountered any serious conflict with structure, elements or definitions of the scheme, and we have been able to accommodate the complete definitions and applications of all 101 lean manufacturing tools and metrics and dozens of manufacturing waste problems.

5. Discussion

This classification scheme can be used in two ways, tool-based or problem-based, both being extremely effective and useful for getting leaner. In its tool-based mode, the classification scheme can be used to define clearly the nature (identification of waste, measurement of waste, elimination of waste, or some combination of these three) and application of each tool. This scheme also provides answers to questions on what type of waste will the tool attack, when to apply it, where to apply it, etc. The tool-based approach for using the classification scheme allows an organization to learn quickly about the tools, their place of application and the type of waste the tool addresses. In the problem-based approach, an organization can use this classification scheme to define its manufacturing problems or sources of waste and then match them with the appropriate lean manufacturing tool or metric. Note that the problem may be a need to identify waste, reduce waste, eliminate waste or measure waste. For example, consider a simple problem occurring in all manufacturing organizations: there is significant wastage of time in searching for the right equipment used for loading or unloading a job from the machine. This problem can be represented by 'we need a tool to eliminate waste due to the inefficiency of time during the performance of the processing of WIP within the job'. Once the problem is represented, one can trace the appropriate elements in the classification scheme to the application level for the set of tools that can alleviate this problem. In this case, the cubby will contain visual control.

With this classification scheme now available, we can re-evaluate the example of tool misapplication discussed above. The company's problem was on-time deliveries. This problem can be classified as 'this is a problem to eliminate waste due to the inefficiency of time during the performance of the processing, transport, inspection, or storage of raw materials, WIP, or finished goods, within the line, cell, or job'. Tracing the appropriate links in the classification scheme, we get possible tools that will eliminate this problem. In this case, it will be load levelling and visual control. This is partially represented in figure 4. Thus, by using this classification scheme, this misapplication would have been prevented. It is important to note that this classification scheme is just an aid to narrow down possible tool choices from 101 to a handful.

6. Conclusions

Our classification scheme is structured around seven levels: system, object, operation, activity, resource, characteristic and application. Each level in turn is broken down into its constitutive elements, some based on prior classification schemes. The levels have been linked systematically so that lean manufacturing tools and metrics, or manufacturing waste problems, are classified by a meaningful and logical 'story'. For example, *pokayoke*—this tool eliminates waste due to the unreliability of machines during the performance of the processing of WIP within the job. We have classified 101 commonly used lean manufacturing tools and metrics as well as dozens of manufacturing problems using this classification scheme. We have not encountered any clashes between the classification-defined nature of tools, metrics, and problems and their intended use or description.

The classification scheme described in this paper can be used to classify lean manufacturing tools and metrics systematically and logically, making tool selection easier for organizations. Given a software tool to do this, it would be extremely useful on the shop floor. This classification scheme can reduce the misuse of tools and metrics or the misapplication of tools at improper locations or for improper purposes. At the same time, this scheme will make it easier for researchers and manufacturing organizations to classify and understand the commonalities among existing manufacturing waste problems and then develop the appropriate tools or metrics attack these problems effectively. Using this classification, we can easily understand the nature of a lean manufacturing tool, or metric, or a manufacturing waste problem, including its level of abstraction, the appropriate location of application in the organization, whether it addresses management waste or activity waste, the type of resource waste it addresses, and whether it identifies waste, measures waste, or a combination of these three. The classification scheme enables us to link manufacturing problems to the appropriate lean manufacturing tools that will solve the problem.

Future work proposed includes a significant industrial validation study of the classification scheme for both wastes and tools. The beginning of this validation process is this paper and readers' response to it. Another area of work on the lean manufacturing classification scheme is the ordering of the tools within each of the roughly 10 000 chains. Ordering the tools by either sequence of use or maximum efficiency would allow for an even finer understanding of which lean manufacturing tools to use when. Finally, we have begun work that expands this method of classification beyond lean manufacturing, using this work as a blue print to define lean in other areas of an organization.

References

Advanced Manufacturing, 2000 [http://www.advancedmanufacturing.com] (19 April).

Barker, R. C., 1994a, Production systems without MRP: a lean time based design. *Omega, International Journal of Management Science*, **22**, 349–360.

Barker, R. C., 1994b, The design of lean manufacturing systems using time-based analysis. *International Journal of Operations and Production Management*, **14**, 86–96.

Boeing Company, 2000, Lean Manufacturing [http://www.boeing.com/] (5 January).

Casti, J. L., 1987, Manufacturing as a system determined science. *Technological Forecasting and Social Change*, **31**, 305–321.

CITEC Manufacturing and Technology Solutions, 2001, Lean manufacturing [http://www.citec.org/lean_manufacturing.html] (5 January).

Connstep, Inc., 2001 [http://www.connstep.com/web/frames.nsf/pages/Products] (28 August).

Cusumano, M. A. and Nobeoka, K., 1998, *Thinking Beyond Lean* (New York: Free Press).

Dillon, A., 1985, *The Sayings of Shigeo Shingo: Key Strategies for Plant Improvement* (Cambridge, MA: Productivity Press).

Dixon, J. R., Duffey, M. R., Irani, R. K., Meunier, K. L. and Orelup, M. F., 1988, A proposed taxonomy of mechanical design problems. Proceedings of the 1988 ASME International Computers in Engineering Conference and Exhibition, San Francisco, CA.

DT Industries, 2000, Lean manufacturing [http://aaadti.com/leanmanufacturing.html] (15 September).

Feld, W. M., 2000, *Lean Manufacturing Tools and Techniques and How to Use Them* (Boca Raton, FL: St Lucie).

Fleischer, M. and Liker, J. K., 1997, *Concurrent Engineering Effectiveness* (Cincinnati, OH: Hanser Gardner).

Gateway2Lean, 2001, Yahoo Message Group, Message 36, Lean implementation hurdles, 18 October.

Green, M. and Dick, M., 2001, Baseline analysis diagnoses manufacturing. *Lean Directions: The e-Newsletter of Lean Manufacturing* (Society of Manufacturing Engineers) [http://www.sme.org/cgi-bin/get-newsletter.pl?LEAN&20010709&1&] (10 July).

Liker, J. K., 1998, *Becoming Lean* (Portland, OR: Productivity Press).

Liker, J. K., Ettlie, J. E. and Campbell, J. C., 1995, *Engineered in Japan* (New York: Oxford University Press).

Mills, J. J., 1993, A taxonomy of the product realization process environment. *Research in Engineering Design: Theory, Applications, and Concurrent Engineering*, **4**, 203–213.

Mueller, S., 1998, Operations and human factors: business processes and innovation [http://www.dig.bris.ac.uk/] (26 November).

Nicholas, J. M., 1998, *Competitive Manufacturing Management* (New York: Irwin McGraw-Hill).

Russell, R. S. and Taylor, B. W., 1999, *Operations Management*, 2nd edn (Upper Saddle River, NJ: Prentice-Hall).

Schonberger, R. J., 1982, *Japanese Manufacturing Techniques: Nine Hidden Lessons in Simplicity* (New York: Free Press).

Search Manufacturing, 2000, Lean manufacturing glossary of terms [http://www.search-manufacturing.com/Manufacturing/Lean/glossary.htm] (10 January).

Shingo, S., 1992, *The Shingo Prize Production Management System: Improving Process Functions* (Cambridge, MA: Productivity Press).

Taylor, D. and Brunt, D., 2001, *Manufacturing Operations and Supply Chain Management: The Lean Approach* (London: Thomson Learning).

Thompson, D. and Mintz, P., 1999, Lean manufacturing [http://www.citec.org/lean_manufacturing.html]. *Business Journal*, 15 December.

Todd, P., 2000, Lean manufacturing: building the lean machine [http://www.advancedmanufacturing.com/leanmanufacturing/part1.htm]. *Advanced Manufacturing*, 12 September.

Womack, J. P. and Jones, D. T., 1996, *Lean Thinking* (New York: Simon & Schuster).

Womack, J. P., Jones, D. T. and Roos, D., 1990, *The Machine That Changed the World* (New York: Macmillan).

Zimmer, L., 2000, Get lean to boost profits. *Forming and Fabricating*, February.