World-Class Engineering: Designing for Quality, Reliability, Maintenance, and Supply Chain Management Using the Analytic Hierarchy Process

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World-Class Engineering: Designing for Quality, Reliability, Maintenance, and Supply Chain Management Using the Analytic Hierarchy Process

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Abstract - **Designing products to meet world-class manufacturing (WCM) objectives requires the consideration of many factors beyond immediate design requirements. Design topology and component selection are integral aspects of the design process that strongly influence performance. They are complex tasks, and the complexity increases dramatically when WCM considerations such as product maintenance and supply chain management are included. This paper demonstrates that multiple-criteria decision analysis techniques such as the analytic hierarchy process (AHP) are well-suited to integrating WCM principles into the design process while alleviating the increased complexity of design decisions. An example is provided based on electronic hardware design. Systematic use of AHP in circuit design increases the quality and value of designs while reducing the cost of development—all of which are WCM objectives.**

Keywords – **Decision-making, design for manufacture, industrial engineering, maintenance engineering, product design**

I. INTRODUCTION

The adoption of world-class manufacturing (WCM) practices (such as total quality management, just-in-time manufacturing, lean manufacturing, and supply chain management) has been shown to reduce costs, foster a culture of continuous improvement, increase customer satisfaction, produce higher quality products, and increase the market shares of the organizations that employ them [1]–[4]. However, most WCM practices focus exclusively on manufacturing processes and supply chain management, ignoring fundamental aspects of product design and development [5]. Because the profitability of WCM can be limited by product design [1], the development process is a "key enabler" for the success of WCM [6], [7].

A critical aspect of product development is component selection [8]. If the wrong components are selected, specifications will not be met. If suboptimal components are chosen, the system will not be world-class. Ideally, specifications and design calculations drive the selection of components and no further evaluation is required. However, after component specifications are determined, there are often hundreds or thousands of available components that meet the requirements, causing the design process to be complicated and time-consuming [9].

Design engineers are inundated with technical challenges and intense pressure to bring to market complex systems of the highest quality and lowest cost as quickly as possible [10], [11]. The technical aspects of design alone can be staggeringly complex. Designing for WCM, however, requires consideration of more than technical performance. System design and component selection may include WCM factors such as complexity (an indicator of quality, maintainability, and manufacturability), cost, supply chain considerations (such as available inventory, standardization, lead time, counterfeit risk, past supplier performance, technology road maps, supplier location, multisourcing risk, life-cycle stage, and supplier relationships), form factors, materials, storage requirements, and packaging compatibility with manufacturing equipment.

In 1956, G. A. Miller famously claimed that the human capacity for simultaneously comparing pieces of information is limited to 7 plus or minus 2 items [12]. More contemporary research suggests this is, at best, an asymptotic limit, and practical limits of 3 to 5 pieces of information are more likely [13]. The quantity of information evaluated during the engineering design process may be orders of magnitude greater than these limits, even without considering WCM objectives [14]. Information overload degrades performance, leads to inefficiencies, decreases the evaluation of available options, and causes inaccurate decision-making [15]–[17]. As such, adding WCM objectives to engineers' existing challenges will prove difficult if engineers are not provided the tools to do so effectively.

Formal decision-making tools have been suggested for achieving WCM objectives, not only from a strategic perspective [18], [19] but also at every level of the design process [20]. This paper shows that multiple-criteria decision analysis (MCDA) methods are highly suited to solve the problem of designing WCM objectives into products while successfully juggling traditional challenges. One of the most well-known and successful MCDA methods is the analytic hierarchy process (AHP), invented by Thomas L. Saaty [21]. AHP has an impressive history of applications from business, finance, political, and military decisions [21] to the selection of semiconductor materials [22] and, more recently, as an algorithm for wireless networking [23].

Systematic use of AHP allows WCM objectives to be designed into the very "DNA" of a product. Employing AHP during the design process fosters the development of systems with the highest possible quality and economy while simultaneously reducing design time—all goals inherent in WCM [7]. The use of AHP offers the following benefits:

- A semi-automatic component selection process that can decrease the decision time and lower development costs [21].
- The analysis of more options than is typically possible, increasing the probability of finding components better suited to the application [8].
- Increased transparency in the component selection process, which allows a more careful consideration of selection criteria [8], [21].
- The opportunity for inexperienced engineers to efficiently harness the experience of seasoned engineers using voting methods for determining criteria importance [8].

Although AHP is applicable to other fields within industrial engineering, this paper explains it in the context of component and design topology selection for electronic hardware design. Both design layers can have a profound impact on WCM performance. An example is provided to illustrate component selection using AHP while incorporating WCM criteria. The results of the example are discussed, showing the increased transparency of the decision-making process. Application of AHP to the selection of a WCM-optimized circuit topology is then demonstrated with a real-world example of a transducer design.

II. Methodology

A. *Identifying WCM-Related Criteria*

AHP has the remarkable ability to quantify and compare a diverse set of criteria. If only electrical criteria are considered, for example, it may be possible to combine the criteria into an overall performance quantity (such as a total accuracy) without AHP. However, designing to meet both WCM objectives and technical requirements requires the consideration of many factors beyond data sheet specifications. This section explains how WCM principles are used as criteria in AHP to improve quality and reliability, maintainability, and supply chain management.

1) Quality and Reliability: A common method of increasing reliability is to select parts that exceed design specifications. Adding margin, however, can increase the price, mass, or volume of a product [24]. Incorporating such criteria into component selection can balance the increased quality and reliability with consideration for the associated costs. For example, the maximum allowable junction temperature of a part may correlate with reliability. But, parts with higher temperature ratings may be significantly more expensive or only available from non-preferred suppliers. AHP can incorporate both reliability and the associated tradeoffs into the decision.

Some component form factors are more susceptible to damage during the manufacturing process and in field applications, potentially decreasing quality and reliability. These quality factors can be included in the component selection decision using AHP by obtaining quality data for each form factor.

2) Product Maintenance: Part obsolescence steals resources from new development and increases design lead times (contrary to WCM objectives [7]). If the circuit is intended to have a long production cycle, estimating the end-of-life (EOL) dates of the individual components is important for mitigating risk. Including an estimated EOL date may be useful to distinguish between, for example, a low-cost part having a high EOL risk and a higher cost part with guaranteed production for the next ten years.

The number of acceptable drop-in replacements for each part is another useful criterion for mitigating risk. It may be desirable to choose a component with slightly worse electrical features than some alternatives but which is in a common package sourced by multiple vendors.

3) Supply Chain Management: The selection and evaluation of suppliers is a critical factor for the success of an organization [25]. AHP has received widespread attention in the supply chain management field and is highly suited to solving the supplier selection problem [25]–[28]. Evaluation of a supplier based on their past performance, current relations, portfolio, and even location (for risk management) is crucial to ensuring high-quality, low-cost designs that can be reliably manufactured and maintained. Suppliers can be ranked on their WCM-compatibility such that components made by preferred suppliers are more likely to be selected than parts from non-preferred suppliers.

Standardization is an important WCM concept [7], and components that are already being used in another product at the organization and for which supplier relations are already well-developed may be given additional weight in the decision.

Parts with no available stock or very few distributors may be undesirable, even if they have excellent characteristics or price, due to the increased risk of being unable to obtain production quantities. Including inventory risk as a factor in part selection reduces the risk of production outages.

Since AHP can incorporate many WCM-related criteria into a decision, components supporting a truly world-class design can be identified. For example, a component made by a “partner in profit” (WCM preferred supplier [7]) but that also has acceptable alternatives from other suppliers (supporting product maintenance goals) is ideal and would be scored accordingly by AHP.

4) Relation of Criteria to WCM: Some WCM ideas are too abstract to be used as criteria directly. This paper uses criteria that *support* WCM objectives. For example, determining the “maintainability” of a resistor may be difficult, but the number of drop-in replacements is quantifiable and supports maintainability. WCM concepts can also create dependency between criteria (e.g., between complexity and reliability) and thus should not be evaluated with AHP directly. In the case of such dependencies, the analytic network process (ANP) is suggested [29].

B. Organizing and Weighting Criteria

Once the criteria are collected, they are organized hierarchically, per AHP. The example below illustrates how WCM-related criteria (marked with †) can be included in the decision with technical criteria.

- Manufacturer rating† (0 to 10)
- Price† ($)
- Part performance
  - Initial accuracy (%)
  - Temperature coefficient (ppm/°C)
  - Long-term stability (ppm/1,000 hr)
- Estimated supply chain risk†
  - Life-cycle risk† (%)
  - Estimated EOL† (years)
  - Multisourcing risk† (number of alternatives)
  - Inventory risk† (number of distributors)
- Footprint area (mm^2)

A pairwise comparison matrix is then created to assign weights to the criteria.

C. Creating a Decision Matrix and Evaluating With AHP

Finally, a decision matrix is created and alternatives are ranked with AHP. For best results, all options in the decision matrix should meet design specifications. Any influence by WCM considerations—such as manufacturer preference, quality, supply chain, features, etc.— must be subordinated to the design specifications.[1] This paper assumes that all options in the decision matrix meet the product or circuit specifications and requirements.

III. EXAMPLES

A. Component Selection

Components are often evaluated only on technical factors, but the following example applies AHP[2] to select a component based on the following two technical criteria and two WCM criteria (marked with †):

- C_1 = Price† ($)
- C_2 = Breakdown voltage (V)
- C_3 = Supplier rating† (1 to 3, with 1 being best)
- C_4 = Has telemetry features (0 or 1)

A pairwise comparison survey for these criteria is shown in Fig. 1. The answers in Fig. 1 are converted to a pairwise comparison matrix in (1).

[1] AHP does work if alternatives that do not meet the design specifications are included. However, this is a waste of time (contrary to WCM principles [7]) and may confuse decision-makers.

[2] AHP is well-known and the details of the process are well-documented [30]. Thus, the example does not explain in detail how to use AHP.

On each line, check the criterion deemed more important than the other. On a scale of 1 to 9, circle the relative importance of each criterion.

1) Price ( ) or Breakdown Voltage (✓)
   1 ② 3 4 5 6 7 8 9
2) Price ( ) or Supplier Rating (✓)
   1 2 3 4 5 ⑥ 7 8 9
3) Price ( ) or Telemetry (✓)
   1 ② 3 4 5 6 7 8 9
4) Breakdown Voltage ( ) or Supplier Rating (✓)
   1 2 3 ④ 5 6 7 8 9
5) Breakdown Voltage ( ) or Telemetry (✓)
   1 2 3 4 ⑤ 6 7 8 9
6) Supplier Rating (✓) or Telemetry ( )
   1 2 ③ 4 5 6 7 8 9

Fig. 1. Example pairwise comparison survey for component selection.

$$\mathbf{C} = \left[\begin{array}{c|cccc} & C_1 & C_2 & C_3 & C_4 \\ \hline C_1 & 1 & 1/2 & 1/6 & 1/2 \\ C_2 & 2 & 1 & 1/4 & 1/5 \\ C_3 & 6 & 4 & 1 & 3 \\ C_4 & 2 & 5 & 1/3 & 1 \end{array}\right] \tag{1}$$

A popular method for extracting weights from a pairwise comparison matrix is to compute the normalized right principle eigenvector [31], as shown in (2).

$$\vec{w} = \begin{bmatrix} 8.49\% \\ 10.88\% \\ 53.49\% \\ 27.14\% \end{bmatrix} \tag{2}$$

In this example, three components meet the specifications. The data matrix is constructed in (3).

$$\mathbf{D}_{\text{example}} = \left[\begin{array}{c|cccc} & C_1 & C_2 & C_3 & C_4 \\ \hline P_1 & \$1.05 & 3.3\,\text{V} & 1 & 1 \\ P_2 & \$2.80 & 9\,\text{V} & 2 & 1 \\ P_3 & \$0.97 & 5\,\text{V} & 1 & 0 \end{array}\right] \tag{3}$$

The list of criteria contains three types of data, which are normalized in (4).

$$\mathbf{N}_{\text{example}} = \left[\begin{array}{c|cccc} & C_1 & C_2 & C_3 & C_4 \\ \hline P_1 & 0.96 & 0.00 & 1.0 & 1 \\ P_2 & 0.00 & 1.00 & 0.5 & 1 \\ P_3 & 1.00 & 0.3 & 1.0 & 0 \end{array}\right] \tag{4}$$

The vector of scores is computed by multiplying (4) by (2), as shown in (5). The component P_1, with a score of 88.78 percent, is the clear winner, with P_3 in second place and P_2 last.

$$\mathbf{N}_{\text{example}} \bullet \vec{w} = \begin{bmatrix} 88.78\% \\ 64.77\% \\ 65.24\% \end{bmatrix} \tag{5}$$

AHP provides unparalleled transparency to the decision [8]. Although P_1 has the lowest breakdown voltage, it is offered at one of the best prices from a highly rated supplier. It also has the desirable telemetry feature. The survey results indicated that breakdown voltage was a relatively unimportant part of the decision, constituting only 10.88 percent of the decision, as shown in (2). This is potentially because all three components already meet a *required* breakdown voltage and derating specification. Although P_3 has an excellent price and competitive breakdown voltage from a highly rated supplier, it lacks the telemetry feature, which constitutes a hefty 27.14 percent of the decision and forces P_3 into second place. P_2 has the best breakdown voltage and the telemetry feature. However, it is the most expensive part from a less-desirable supplier. Combined, price and supplier rating constitute 61.98 percent of the decision, pushing P_2 to last place. Despite the desirable data sheet specifications of P_2, the price and supplier risks—both WCM-related criteria—outweigh the electrical benefits.

B. Design Topology Selection

Even if all components in a design are optimal for the application and WCM, the design itself is not necessarily optimal [1], [7]. Designs that require extensive multilevel processing, have an excessive part count or complexity, or pose a high degree of difficulty for assembly and processing do not contribute positively to WCM initiatives, even if individual components have been carefully selected with WCM in mind. Some WCM principles (such as simplicity and manufacturability) are best considered at the topological level, while other considerations (such as supply chain ramifications and component-specific quality issues) are best considered during the component selection process. Many aspects of a design topology can be evaluated in the same manner as component selection.

For example, the author was asked to design a transducer circuit. The design requirements included a wide dynamic range, high accuracy, and a long time to saturation. Based on these criteria alone, a complex circuit consisting of 213 components was initially proposed. Other designs meeting the requirements were then researched. Four engineers experienced in transducer design filled out a pairwise comparison matrix for eight criteria, and their averaged responses produced the weights in Table I.

TABLE I
TRANSDUCER DESIGN TOPOLOGY CRITERIA WEIGHTS

Criterion	Weight	Relation to WCM
Number of components	17.2%	Simplicity [7]
Power dissipation (PD)	14.8%	Reliability [20]
Circuit size	15.5%	Modularity [7]
Circuit cost	13.5%	Waste [7], [10]
Accuracy over temperature	10.4%	N/A
Dynamic range (DR)	10.0%	N/A
Saturation time (Type A)	9.8%	N/A
Saturation time (Type B)	8.8%	N/A

The performance of each design option was analyzed using AHP (see Table II). The option first proposed, Design G, received the lowest score. Although it met the required specifications, the AHP analysis revealed options more compatible with WCM. Design E exhibited the best technical performance but received a low score due to its high complexity, cost, size, and power dissipation—all criteria supporting WCM objectives. Although Design A received the highest score, it was unknown when Design G was initially proposed; Design A was discovered only during the process of employing AHP. This demonstrates that formal decision-making processes, by reducing the information load, can encourage the evaluation of more options and increase the probability of finding one perfectly suited to the application [8].

IV. CONCLUSION

Designing for WCM yields clear rewards. However, engineering design is a complex undertaking even without considering WCM principles during the design process. Adding WCM considerations to an already time-consuming and complex process may lead to the pitfalls associated with information overload. This paper suggests that a major difficulty in applying WCM principles to design occurs during decision-making processes. AHP has proven valuable in a wide variety of applications where complex decisions are required. AHP can dramatically decrease the time required for decision-making while increasing transparency, confidence, and the number of criteria considered. This paper shows how formal decision-making tools such as AHP enable world-class engineering.

TABLE II
AHP COMPARISON OF TRANSDUCER DESIGNS

Design	Circuit Cost ($)	Number of Components	Circuit Size (mm^2)	Accuracy Over Temperature (%)	Saturation Time (Type A)	Saturation Time (Type B)	DR (dB)	PD (mW)	Normalized Score (%)
A	$0.14	9	3.00	0.373	2.50	1.50	89.50	40.00	100.0
B	$1.60	66	8.12	0.373	2.50	1.50	103.5	40.00	89.93
C	$0.14	9	3.00	0.613	1.53	1.34	89.50	40.00	71.61
D	$1.60	66	8.12	0.613	1.53	1.34	103.5	98.60	61.53
E	$3.59	183	13.53	0.373	3.57	1.65	103.5	98.60	56.93
F	$2.05	120	10.95	0.633	1.71	1.46	89.50	98.60	25.80
G	$4.06	213	14.60	0.633	1.71	1.46	103.5	158.6	0.000

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