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ORIGINAL PAPER

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# A hybrid methodology for enhancing reliability of large systems in conceptual design and its application to the design of a multiphase flow station

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**Abstract** This paper presents a hybrid methodology for conceptual design of large systems with the goal of enhancing system reliability. It integrates the features of several design methodologies and maintenance planning concepts with the traditional reliability analysis. The methodology considers the temporal quality characteristic "reliability" as the main objective and determines the optimal system design. Key ideas from several design methodologies, namely axiomatic design, robust design, and the theory of inventive problem solving, have been integrated with the functional prioritization framework provided by reliability-centered maintenance. A case study of the conceptual design of a multiphase pumping station for crude oil production is presented. The methodology provides a new design tool for determining system configurations with enhanced reliability taking into account maintenance resources and variability.

**Keywords** Reliability; Axiomatic design; Robust design; TRIZ; RCM; Multiphase pump; Crude oil production

## 1 Introduction

The reliability of a system is the probability that the system performs its intended function in an operational context for a specific period. At the design phase, the system reliability is established as a quality characteristic of the system. It cannot be further improved in service without modifying the original design or dramatically increasing the operation or maintenance cost. It is therefore critical to design a system with the highest possible reliability at the design phase.

Depending on the criticality of a product or system, the failure to obtain designed reliability can have many adverse effects ranging from unsatisfied customers to catastrophic events with fatal consequences. A key objective of reliability analysis is to understand and eliminate the conditions that could generate failures or performance degradation. In modern design practice, reliability analysis is routinely conducted based on the intended product or system functions and their operational contexts; however, failures still occur due to reasons such as the deviation from the nominal operational procedures. For example, experience obtained in the oil industry indicates that an important part of the failure events associated with oil wells and pumping stations can be attributed to the inconsistency between the designed and actual operational context in which these equipment and installations have to operate. During the operation, the equipment maintenance schedules suggested by vendors are often not followed due to tight production schedule or limited financial and human resources. As a result, the system design and maintenance schedules are completely detached, leaving the system reliability vulnerable to operational variations.

We propose a new methodology for enhancing the reliability of large systems during the system operation. The driving philosophy of this methodology is to maximize the reliability at the conceptual design stage and to estimate the required resources within the period in which a product or system will perform a set of desired functions. The new methodology goes beyond the application of technical codes and standards. It focuses on the operational and maintenance activities. By bringing the reliability and maintenance considerations early in the conceptual design stage, higher reliability and lower cost in the actual operation and maintenance of the system will be achieved.

In this paper, we demonstrate the new design methodology, which allows the identification, analysis and correction of aspects of product, process, or system that are likely to have reliability failures. We show how to avoid taking for granted the perfect performance in components, equipment, or sub-systems during the conceptual design process. Successful design methodol-

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ogies, namely axiomatic design, robust design, and theory of inventive problem solving (TRIZ), are integrated with the functional prioritization framework provided by reliability-centered maintenance (RCM). The proposed methodology provides a new design tool for determining system configuration with enhanced reliability taking into account maintenance resource and variability.

## 2 Related methodologies

A brief review of the basic characteristics of each methodology considered in the proposed approach is presented in this section.

### 2.1 Axiomatic design

Axiomatic design had its beginnings in 1978, when Suh et al. (1978) proposed a bold hypothesis: "there exists a small set of global principles, or axioms, which can be applied to decisions made throughout the synthesis of a manufacturing system. These axioms constitute guidelines or decision rules which lead to correct decisions, i.e., those which maximize the productivity of the total manufacturing system, in all cases."

In that ground-breaking paper, the authors proposed seven "hypothetical axioms," which after trial and evaluation in manufacturing case studies were distilled to the following two fundamental axioms (Rinderle and Suh 1982):

1. The independence axiom: maintain the independence of functional requirements (FR).
2. The information axiom: minimize information content.

The notion of FRs is more precise in the context of axiomatic design than the more common descriptions of a design task such as "design requirements" or "design objectives." The FRs need to be independent, i.e., it must be possible to state each FRs without regard to other FRs. Careful definition of the design problem in terms of a set of FRs that are consistent and free from redundancy is at the heart of the axiomatic design approach. Details of the axiomatic design methodology and many case studies can be found in Suh (1990, 2001).

In axiomatic design, the need of the customer is translated into the designer language in a set of FRs. These FRs must be associated with the design parameters (DPs) that will satisfy the FRs in the physical space. To limit the solution space, the axiomatic design methodology uses the concept of constraints that differ from the FRs. The constraints cannot be changed or controlled by the designer or design team. The design process progresses from the system level to more detailed levels. The first set of FRs translates the need of the customer into specific elements or components in the physical space. The design process is represented with a design hierarchy. A specific design is composed of hierarchies in each of the domains of FRs and physical DPs.

The process to apply the design axioms has been illustrated by Gebala and Suh (1992). The first axiom requires that the FR be satisfied individually by their corresponding DPs. The second axiom intends to maximize the probability of an item to be manufactured successfully. The design axioms provide a framework to indicate the adequacy of proposed designs. They are used for considering, evaluating, and comparing different alternatives to satisfy the needs or requirements of a specific product or system.

A key benefit of the axiomatic design approach is the structured development of the design problem formulation. This effort leads to a better understanding of the customer requirements and their relative importance. On the other hand, the axiomatic approach is difficult to apply at the detailed levels of the design, where the application of related codes, standards, and engineering practices are often more efficient than the iterative application of the design axioms.

### 2.2 Robust design

Robust design has proven to be very effective for improving quality, manufacturability, and reliability of products and processes at low cost. Since its introduction by Taguchi in the 1980s, the method has resulted in significant quality improvement in many industries (Taguchi 1987; Phadke 1989).

The objective of robust design is to determine the settings of easy-to-control variables (control factors) to achieve the best product or process performance that is insensitive to the variability of hard-to-control variables (noise factors). To achieve this objective, Taguchi recommends performing experiments in which the settings of control and noise factors are determined using orthogonal arrays (Taguchi 1987). A predefined signal-to-noise ratio (S/N) is used as the response of the experiment. The goal of the robust design is to maximize the S/N by choosing appropriate control factor settings.

The most important advantages of robust design include providing a simple and systematic framework for identifying critical characteristics in products or systems and achieving best quality characteristics while minimizing the variation and cost.

### 2.3 Theory of inventive problem solving (TRIZ)

TRIZ is the Russian acronym for the theory of inventive problem solving, introduced by Genrich Altshuller in 1946. The methodology is well documented by Terninko et al. (1998). TRIZ is based on the following postulate: the evolution of a technical system is governed by objective laws and during the evolution the part of the technical system having already reached its pinnacle of functional performance will lead to conflicts with another part, resulting in an eventual improvement of the less evolved part. According to TRIZ everything that performs a function is a technical system and any technical system can consist of one or more sub-systems, performing their own functions. A technical system that produces inadequate or harmful functions can be improved using TRIZ.

Conventional engineering thoughts indicate that when a system is designed to provide some function, the design problem is formulated as: It is required to deliver this function; therefore this mechanism must be built. On the other hand, the statement under the TRIZ approach is that it is required to deliver this function without introducing a new mechanism or device into the system. This concept introduces what is called the Law of Ideality. It states that any technical system, throughout its lifetime, that tends to become more reliable, simple, and effective, is more ideal. According to TRIZ, every time a system is improved, it is getting closer to ideality. It costs less and requires less space and energy.

An important element in TRIZ is contradiction. The concept is exploited based on the assumption that contradictions occur when a characteristic is being attempted to be improved and this improvement cause another characteristic, or parameter, of the system to deteriorate. A compromise is then usually considered. There are three main tools in TRIZ methodology. They are principles, standards, and ARIZ.

*Principles* Forty generic suggestions (Tate and Domp 1997) for performing an action in order to improve the system or solve a problem.

*Standards* Structured rules for the synthesis and reconstruction of systems, providing two main functions:

- Helping to improve an existing system or synthesize a new one.
- Providing the most effective method for a graphical model of a problem (also known as substance-field modeling or S-field modeling). The S-field modeling of a system is performed in the operating zone where the actual contradiction occurs. In this zone, two substances (elements) and a field (energy) must be present. Analyzing the S-field models allows the determination of changes in the system necessary for improvement.

*ARIZ (algorithm to solve an inventive problem)* The central analytical tool of TRIZ, providing specific sequential steps for developing solutions to complex problems.

## 2.4 Reliability centered maintenance

Reliability-centered maintenance (RCM) is a systematic process of preserving a system's function by selecting and applying adequate maintenance or operation where and when it is needed (Mubray 1997). RCM governs the maintenance policy at the level of system or equipment selection. In general, the concept of RCM is applicable to large and complex systems such as automobiles, aircrafts, and chemical plants.

RCM is focused on preserving system functions by identifying, characterizing, and prioritizing the failure modes that can cause respective functional failures. Critical knowledge for implementing adequate measures needs to be generated and applied in a comprehensive set of actions or tasks to preserve the system functions. As described by Mubray (1997), the application of RCM is associated with the application of seven basic steps:

1. identification of functions and their associated desired performance standards;
2. definition of functional failure;
3. identification of failure modes;
4. documentation of the effects of failure;
5. quantification of failure;
6. analysis of functions, functional failures, failure modes, and their criticality to identify opportunities for improving performance and/or safety;
7. establishment of maintenance tasks.

Once the described methodology is applied, not only is the desired optimization of maintenance and operational resources of the system achieved, but also the following:

- greater safety and environmental integrity;
- longer useful life of equipment, due to carefully focused emphasis on the use of on-condition maintenance;
- a comprehensive database of failure modes and actions to prevent them;
- optimal spare parts inventory.

## 2.5 A comparative look at basic methodologies

Although all the above approaches follow the same philosophy, i.e., to maximize fitness for use and satisfaction of customer need, each of these approaches has its own unique features that make it only suitable for a particular aspect in the design process. Comparisons among these approaches have been previously presented (Suh 1990; Hu et al. 2000a, b; Yang and Zhang 2000); however, none of the previous studies has focused on the system reliability.

In this study, we take a comparative look at the basic methodologies with focus on the system reliability. Table 1 summarizes the comparisons. Two major conflicts have been identified among the existing methodologies related to the system reliability.

The first conflict is between axiomatic design and RCM. In axiomatic design, all the FRs at a given level have the same importance; therefore, all the FRs must be satisfied independently regardless of their criticality or failure consequences. On the other hand, the FRs in

**Table 1** Comparison of the general features of various methodologies

| Methodology | Main objective | Functional requirement | Design parameter | Constraint | Main output |
|---|---|---|---|---|---|
| Axiomatic design | Optimal design | Technical interpretation of the customer need | Physical solution to satisfy FRs | Requirement limitations not controlled by the designer | Satisfaction of customer need |
| Robust design | Minimize variability | Output quality characteristic | Controllable factors that affect the quality characteristics | Uncontrollable factors or noise | Robustness of the quality characteristics |
| TRIZ | Solve technical problems | Technical interpretation of the customer need | Physical solution to satisfy FRs | Not defined | Contradiction elimination and technical improvement |
| RCM | Maximize reliability | Desired output of each asset or component in the system | Malfunctioning components which could generate a failure mode | Part of the operational context | Set of tasks to maximize reliability |

RCM should be assigned with priority based on their consequences of failures. The most important FRs should be those failure modes that have consequences on safety or the environment.

This conflict can be further explained using an example. Let us analyze a design problem where the storage of a certain volume ($V$) of natural gas at certain pressure ($P_i$) is required. The application of axiomatic design could establish the following set of FRs:

*FR1* Store volume ($V$) of natural gas at a pressure of $P_i$.

*FR2* Keep the maximum pressure under $P_m$.

A possible solution for this set of FRs could have the following DPs:

*DP1* Cylindrical metallic tank.

*DP2* Safety valve set at $P_m$.

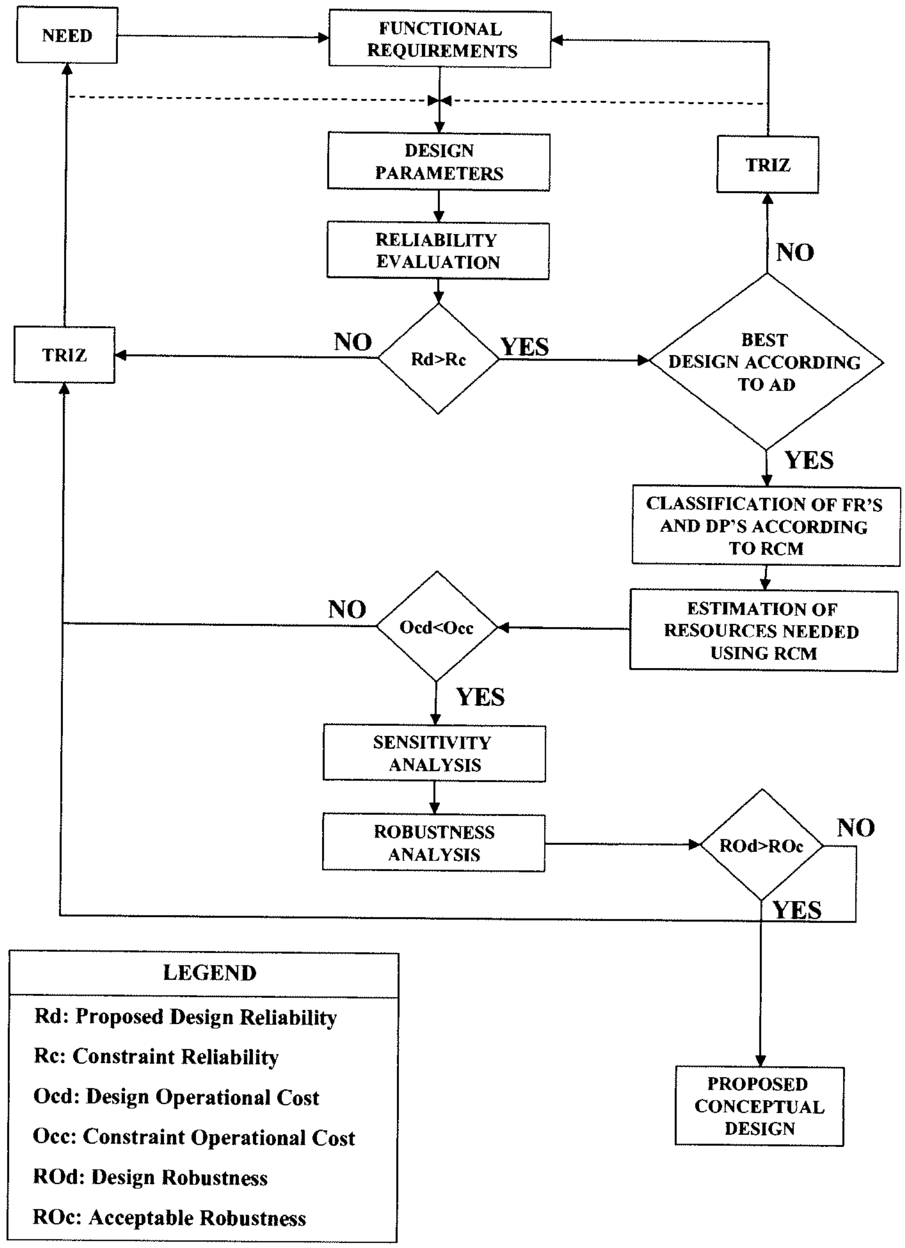
Obviously, both FRs are important and are satisfied by the DPs. Axiomatic design does not require further classification of FRs. From the point of view of RCM, it is obvious that the FR associated with the safety valve is more important. This is because it has a hidden failure mode. RCM systematically classifies the FRs according to their objective within the system and the consequences of their failures. Axiomatic design, on the contrary, does not have a methodological approach for establishing priorities.

The second conflict is related to the concept of coupling and the different approaches that axiomatic design and TRIZ take. In axiomatic design the emphasis is on avoiding coupling in the functional space; however, in TRIZ, the concept of coupling is equivalent to a contradiction that needs be addressed using an analytical tool, called contradiction analysis. TRIZ takes advantage of contradictions to improve the design by eliminating them. This usually involves the elimination of the coupling. Mann (2002) described examples for which contradictions were analyzed differently using axiomatic design and TRIZ. Axiomatic design tries to avoid couplings or to reconfigure the system to minimize their effects, whereas TRIZ faces the couplings and eliminates them in a proactive approach.

## 3 The proposed hybrid methodology

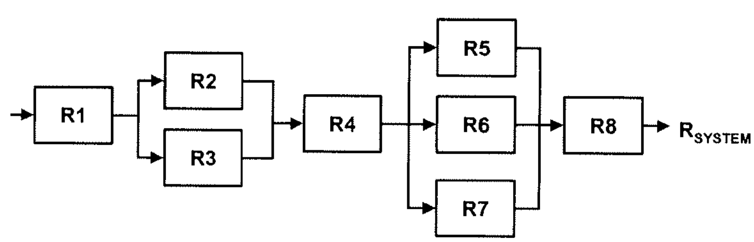
The proposed new methodology is outlined in Fig. 1. The flow diagram indicates the steps in the application of this new approach. These steps begin with the conceptual design, in which the need of the customer is translated into the FRs. At this point, the system reliability is considered simply as an additional constraint. This ensures that the designer recognizes the eventual failure of the system and establishes the expected values for the system reliability.

Fig. 1 Flow diagram of the proposed methodology




In the conceptual design process, axiomatic design principles are applied to allow the designer to achieve the best and yet simplest design. The new methodology does not have an explicit axiom, theorem, or corollary to force the designer to consider the system reliability. However, the design must satisfy the customer need considering the cost, which can be a consequence of the system reliability. Once the FRs and DPs are established, the conceptual design must be evaluated to determine if the initial customer need is satisfied within the constraints. At the

Fig. 2 Reliability block diagram



same time, an evaluation of the reliability can be performed to determine its satisfaction level.

In order to evaluate the reliability of the system, a widely used approach, the reliability block diagram (RBD), can be applied. RBD represents the interaction among the components and sub-systems to fulfill a specific function of the whole system. The reliability of each FR at a level is the result of the reliabilities of the sub-systems or components at the next level, as shown in Fig. 2.

In case the reliability constraint is not satisfied, the designer or design team must reconfigure the system. Usually this process will generate contradictions in the DPs or FRs, which needs to be solved based upon the experience of the design team. At this point it will be useful to consider the use of the TRIZ 40 design principles as described by Tate and Domp (1997). These practical rules are helpful in changing the perspective of the design solution, therefore generating an alternative to the original design in order to satisfy the constraints (in this case the reliability constraint). Once the conceptual design is modified, re-evaluation of the reliability is needed to verify that the reliability goal is satisfied.

Notice that the reliability evaluation can be developed in two ways (Kapur and Lamberson 1997; Dodson and Nolan 1999):

1. Assume certain reliability for each sub-system or component and calculate the system reliability according to the block diagram in Fig. 2. If the reliability constraint is satisfied, the design is feasible.
2. Given the reliability required for the FRs at the first level of the design, use the block diagram in Fig. 3 to allocate the reliability for each component or sub-system. If the first set of reliability is within specification and the component or sub-system reliabilities are achievable, the design is feasible.

Once the conceptual design is completed, it is necessary to establish what resources are needed to keep the functionality and reliability of the system at the required levels. This requirement calls for a maintenance and operations plan. The ideal tool to identify activities and resources needed for a maintenance plan is RCM. Because FRs were previously established using axiomatic design, the application of RCM will simply involve two tasks. The first task is the classification of FRs based on their failure consequences, safety and environmental consequences, and operational and/or non-operational consequences. The second task is the identification of the failure modes and effect analysis on a decision sheet, where the activities to maximize reliability are established with their required resources. The systematic application of RCM will result in prioritized FRs at each level of the conceptual design, identification of failure modes for each FR, and initial identification of maintenance, operational activities, and required resources to keep the reliability level of the design as desired.

At this point, the design team has not only established the conceptual design solution but also calculated the expected reliability and resources needed to keep the system running within specifications. If the resources needed are achievable, the design process can continue to the next step. If not, the contradiction can be solved again using the framework of TRIZ. Depending on the complexities of the design, it may be necessary to perform one or more design iterations.

Assuming the resources needed are achievable, it should be recognized that the design generated is based on the assumptions of specific operational context

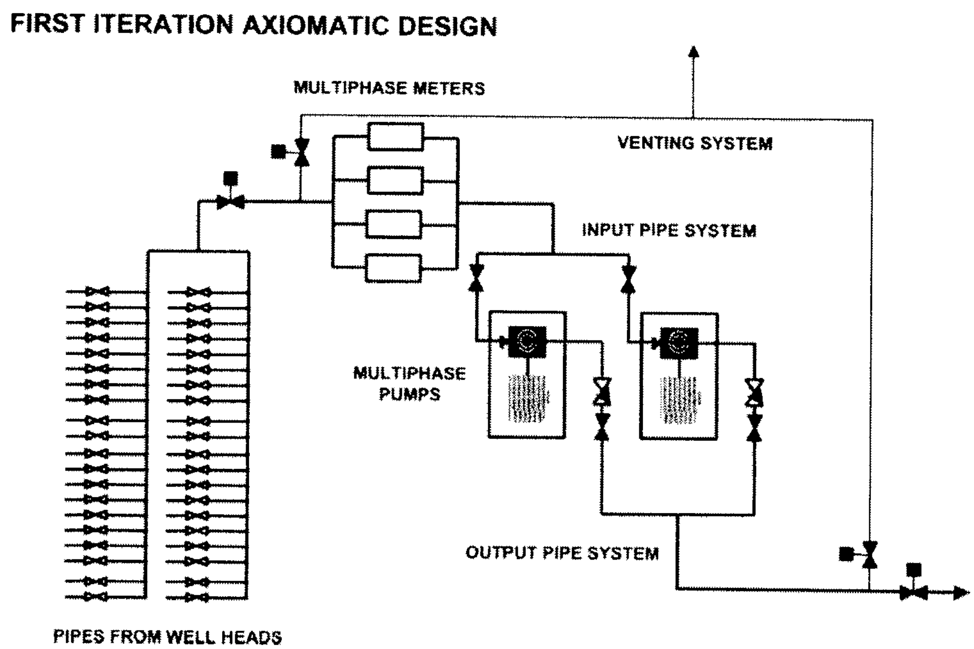



Fig. 3 Conceptual design first iteration

including the operational conditions, maintenance schedules, and other resources. This operational context could change during real operations. Therefore, it is important to determine how robust the system is under the variation of operational context. The ideal tool to achieve this goal is robust design.

Robust design will allow the design team to identify what is the response level of the system's reliability through an equivalent output variable such as mean-time between-failures (MTBF) or running life in different scenarios of the resources and/or physical operation conditions. Considering different scenarios during the early stages of the design process eliminates the limitations of RCM in terms of validation requirement under different operational contexts.

If the robustness of the system is satisfactory, the conceptual design process has generated all the necessary information for a reliable design in its detailed design phase. On the other hand, if contradictions arise, they must be solved using the TRIZ framework.

It is now important to discuss how the basic concepts of design will be managed through the application of the hybrid methodology, specifically, the FRs, DPs, and constraints, given the differences of their characteristics among the methodologies involved.

*FRs* The FRs as originally defined by axiomatic design will remain during the whole process unless a change is required for achieving a better design. Although the original definition will be used for axiomatic design, TRIZ, robust design and RCM, it is important to notice that the FRs used after the axiomatic design are those corresponding to the lowest level developed in the design process.

*DPs* The DPs will represent different elements as defined in Table 1. However, within the framework of the hybrid methodology, the DPs will remain as defined by axiomatic design unless a change in the FRs generates a change in the DPs. For the application of RCM the failure modes will be associated to the DPs at the lowest level of the hierarchical design process.

*Constraint* The constraint as defined by the axiomatic design will remain the same through the application of the hybrid methodology and can be interpreted simply as conditions to be met by the system. However, for the application of robust design the constraint of reliability is transformed indirectly to the output response through the MTBF.

Table 2 summarizes the treatments of design elements in the hybrid methodology. As can be seen, axiomatic design is the basis for the application of TRIZ, robust design and RCM. In fact, the main idea of the proposed methodology is to formulate an axiomatic design framework as a tool for maximizing the system reliability early in the design process.

## 4 Case study

In this section, the proposed approach is demonstrated using a case study for the design of a multiphase flow station in the oil industry.

### 4.1 Multiphase flow station

The traditional oil production begins with the identification of hydrocarbon reservoirs and the posterior extraction from the sub-surface by drilling and displacing production wells on the field. Once on surface the extracted oil is processed into a fluid with certain chemicals and physical characteristics specified by the refineries or posterior transformation processes (Jahn et al. 1998). The basic operations after the oil is extracted are the dehydration and separation from gas, for which specific installations are required. These installations include flow stations, treatment stations, compression plants, and water plants.

**Table 2** Treatment of design elements

| Methodology | Functional requirement | Design parameter | Constraint (reliability) |
|---|---|---|---|
| Axiomatic design | The need is translated into the definitions of functional requirements | Definition of elements required for complying with functional requirements within the physical space | Identified and used as a main element for limiting the solution space. Reliability is used as a main constraint |
| TRIZ | Identification and resolutions of contradictions | Identification and resolutions of contradictions | Reliability is used as a parameter for defining contradictions and appropriate solutions |
| RCM | Used as primary and secondary functional requirements | Used for the definition of failure modes that affects the functional requirements | Used as valid information for defining the consequences of failure modes and identifying appropriate maintenance tasks |
| Robust design | Used to define the experiment required | The maintenance tasks defined in RCM are used for defining the control factors and their levels | Used as a response variable (MTBF) |

In a typical oil production system, the fluids from the wellheads are gathered by the flow stations, where the gas content of the oil is removed in order to transfer the liquid oil to the treatment stations. This is required because the traditional surface pumping equipment, such as the centrifugal pumps, conventional screw pumps, and reciprocating pumps, are not able to safely and efficiently energize multiphase fluids and transport them through long distances, especially for the gas phase. Additional equipment such as tanks and separators are required to perform the gas–liquid phase separation. Once the liquid and gaseous phases are separated, the gas is sent to compression plants and the liquid is sent to the treatment stations where the residual gases as well as water are removed from the oil. Then again, the gases are sent to the compression plants and the water is sent to the water plants. The clean oil is then sent to a storage facility waiting to be transferred to a refinery or other downstream processes.

As can be seen from the above, the traditional oil production installations are not efficient because of many redundant pieces of equipment for gas–liquid separation and storage. One alternative to the traditional approach is the multiphase flow station approach. In this approach, the fluids from wellheads are directly pumped to distant locations, where bigger and more centralized treatment stations can be built for more efficient phase separation. This new installation results in obvious savings in equipment, operation, and maintenance costs. It also generates savings in piping and associated installations such as compression plants and water plants (Scott and Martin 2001).

The use of the multiphase technology for transferring oil to long distances is relatively new. There are still many issues related to the multiphase pump itself, such as vibration control, mechanical seals, upstream and downstream slugs, and the design of associated subsystems. This paper presents a case study on the design of an oil production system using the multiphase flow technology. The purpose here is to illustrate how to apply the proposed hybrid design methodology presented in the previous section. The technical specifications of the multiphase pump, instrumentation, and accessories used in the paper are assumed based on the authors' past experience.

**Table 3** Design parameters

| Parameter | Value |
|---|---|
| Number of oil wells | 20 |
| Average suction pressure | 75 psi |
| Required discharge pressure | 400 psi |
| Volume of gas | 4 mscf |
| Volume of oil | 25,000 bpd |
| Volume of water | 2500 bpd |
| Suction temperature | 100°F |
| Total equivalent volume | 161 boepd |

*Note*: Details about the physical and chemical properties of the fluids are not considered*psi* pounds per square inches, *mscf* million of standard cubic feet, *bpd* barrels per day, *boepd* barrels of oil equivalent per day

## 4.2 Design of a multiphase flow station

The design activity goes through several iterations according to the proposed hybrid methodology.

**Table 4** Axiomatic design (first iteration)

| FR1 | Transfer 162 boepd of oil from a well cluster to a treatment station |
|---|---|
| DP1 | Boosting system |
| FR11 | Gather all entering fluids to a single current |
| DP11 | Suction system |
| FR111 | Contain fluids to pressures up to 150 psi |
| DP111a | Thickness of pipe |
| DP111b | Material of pipe |
| FR112 | Collect fluids from wells as desired |
| DP112a | Valves per well |
| DP112b | Pipe arrangement |
| FR113 | Supply fluid to each pump as desired |
| DP113a | Valves per pump |
| DP113b | Pipe arrangement |
| FR12 | Deliver fluids at the required discharge pressure |
| DP12 | Two twin screw pumps |
| FR13 | Gather all exiting fluids to a single current |
| DP13 | Discharge system (2 to 1) |
| FR131 | Contain fluids to pressures up to 500 psi |
| DP131a | Thickness of pipe |
| DP131b | Material of pipe |
| FR132 | Collect fluids from pumps as desired |
| DP132a | Valves per pump |
| DP132b | Pipe arrangement |
| FR133 | Avoid return of fluids to the pumps |
| DP133 | Check valve per pump |
| FR2 | Measure the quantity of fluids transferred |
| DP2 | Metering system |
| FR21 | Quantify flow of gas |
| DP21 | Four multiphase flow devices |
| FR22 | Quantify flow of oil |
| DP21 | Four multiphase flow devices |
| FR23 | Quantify flow of water |
| DP21 | Four multiphase flow devices |
| FR3 | Protect the system against explosion or fire events |
| DP3 | Fire protection system (philosophy of compression plant) |
| FR31 | Avoid over pressure in the system |
| DP31 | Relief system |
| FR311 | Detect high-pressure condition (suction and discharge) |
| DP311 | Pressure switch |
| FR312 | Reduce pressure |
| DP312 | Relief valves |
| FR32 | Avoid presence of combustible materials in case of fire |
| DP32 | Vacuum system |
| FR321 | Detect fire condition |
| DP321 | Fire detectors |
| FR322 | Discharge pressure |
| DP322 | Relief valves |
| FR323 | Block the entrance of new fluids into the installation |
| DP323 | Blocking valves |

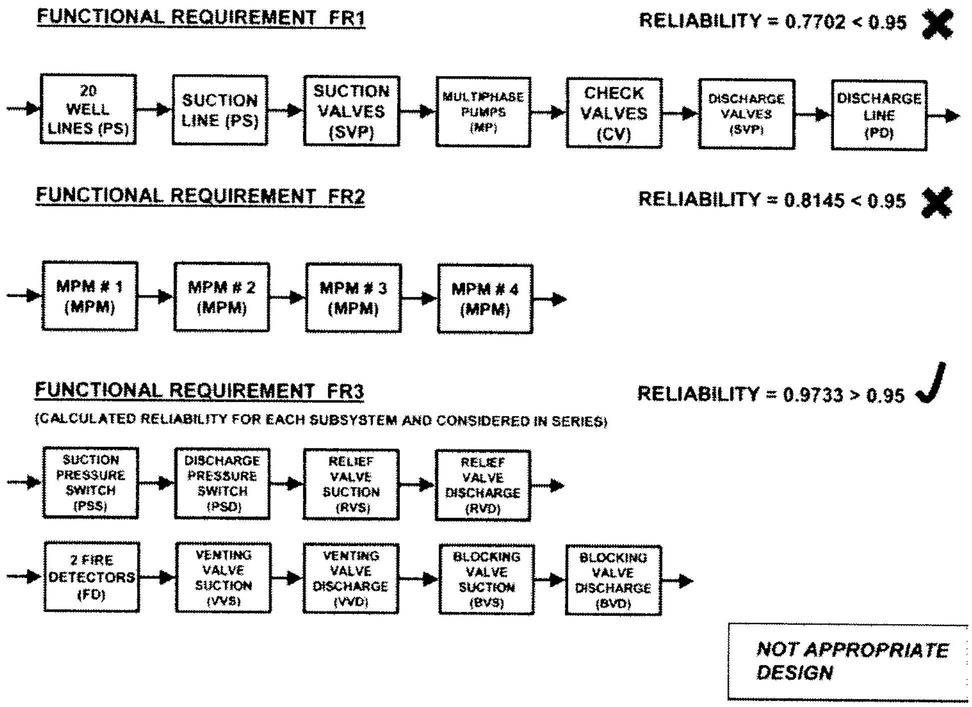



**Fig. 4** Block diagram for the first iteration

### *4.2.1 Axiomatic design (first iteration)*

To start the design process, the customer need must be clearly identified. In this case, the need is to transport wellhead fluids to a treatment station with the maximum safety, minimum cost, and ability to monitor and control the fluids being transported. This need is associated with a series of DPs that define the characteristics of the solution required. Table 3 lists these DPs.

The constraint considered in this study will be the reliability of the designed system. It should be noticed that the reliability is only one of many constraints that could be considered in this case study. Other constraints may include cost, construction time, environmental impact, and human resources. For this case study, we will use a minimum reliability of 95% (at 100 h of operation) as a constraint for the system design.

Once all the elements required to begin the design process are available, axiomatic design can be applied for the first iteration to produce a set of FRs and DPs, as listed in Table 4. Notice that in designing an installation, the design team usually does not have access to the exact specifications of particular components of the system, such as the pipes, valves, pumps, filters, and instruments. Consequently, the design process continues up to the equipment level. However, the design team must verify if the specifications of the equipment are compatible with the system designed.

In this case study, the information axiom was not explicitly applied; however, this does not mean that the application of these axioms is not recommended. On the contrary, the information axiom can be very useful in those cases in which there are two or more solutions that can satisfy the constraints successfully. In such cases, the selection of the final solution will greatly depend on the information content of each solution.

**Table 5** Component reliability

| Component | ID | Reliability |
|---|---|---|
| Sectioning valves per well | SVW | 0.999 |
| Sectioning valves per pump | SVP | 0.999 |
| Relief valves suction | RVS | 0.999 |
| Relief valves discharge | RVD | 0.999 |
| Venting valve suction | VVS | 0.999 |
| Venting valve discharge | VVD | 0.999 |
| Automatic valves | AV | 0.99 |
| Multiphase meters | MPM | 0.95 |
| Multiphase pumps | MP | 0.89 |
| Pipes | PS | 0.999 |
| Pipes | PD | 0.999 |
| Pressure switches | PSS | 0.99 |
| Pressure switches | PSD | 0.99 |
| Check valves | CV | 0.999 |
| Fire detectors | FD | 0.999 |
| Blocking valves | BV | 0.999 |
| Blocking valve suction | BVS | 0.999 |
| Blocking valve discharge | BVD | 0.999 |

### *4.2.2 Reliability evaluation (first iteration)*

To estimate the reliability of the installation, it is required to transform the conceptual design described in the previous section into a graphical representation of the physical components as shown in Fig. 3. A block diagram is also constructed as shown in Fig. 4 to evaluate the design of the first iteration in the reliability

**Table 6** Axiomatic design (second iteration)

| FR1 | Transfer 162 boepd of oil from a well cluster to a treatment station |
|---|---|
| DP1 | Boosting system |
| FR11 | Gather all entering fluids to a single current |
| DP11 | Suction system |
| FR111 | Contain fluids to pressures up to 150 psi |
| DP111a | Thickness of pipe |
| DP111b | Material of pipe |
| FR112 | Collect fluids from wells as desired |
| DP112a | Valves per well |
| DP112b | Pipe arrangement |
| FR113 | Supply fluid to each pump as desired |
| DP113a | Valves per pump |
| DP113b | Pipe arrangement |
| FR12 | Deliver fluids at the required discharge pressure |
| DP12 | Two twin screw pumps |
| FR13 | Gather all exiting fluids to a single current |
| DP13 | Discharge system (2 to 1) |
| FR131 | Contain fluids to pressures up to 500 psi |
| DP131a | Thickness of pipe |
| DP131b | Material of pipe |
| FR132 | Collect fluids from pumps as desired |
| DP132a | Valves per pump |
| DP132b | Pipe arrangement |
| FR133 | Avoid return of fluids to the pumps |
| DP133 | Check valve per pump |
| FR14 | Continue the transfer of fluids in case of failure in one pump |
| DP14 | Stand-by unit |
| FR2 | Measure the quantity of fluids transferred |
| DP2 | Metering system |
| FR21 | Quantify flow of gas |
| DP21 | (4 of 6) Multiphase flow devices |
| FR22 | Quantify flow of oil |
| DP21 | (4 of 6) Multiphase flow devices |
| FR23 | Quantify flow of water |
| DP21 | (4 of 6) Multiphase flow devices |
| FR3 | Protect the system against explosion or fire events |
| DP3 | Fire protection system (philosophy of compression plant) |
| FR31 | Avoid over pressure in the system |
| DP31 | Relief system |
| FR311 | Detect high-pressure condition (suction and discharge) |
| DP311 | Pressure switch |
| FR312 | Reduce pressure |
| DP312 | Relief valves |
| FR32 | Avoid presence of combustible materials in case of fire |
| DP32 | Vacuum system |
| FR321 | Detect fire condition |
| DP321 | Fire detectors |
| FR322 | Discharge pressure |
| DP322 | Relief valves |
| FR323 | Block the entrance of new fluids into the installation |
| DP323 | Blocking valves |

space. Notice that the constraint in reliability will be applied to each FR. In this case, it is required that the reliability for each FR is at least 95%. The calculation for the reliability of each FRs is done based on the traditional reliability theory. The reliability for each component is listed in Table 5. The exponential distribution is assumed for the reliability function of these components.

As showed in Fig. 4, the reliability constraint is not satisfied for FRs I and II. The options for improving the design are: (1) To identify the components with higher reliability in order to increase the FR, and (2) to modify the interaction of the components. The second option implies redesigning the system. In this particular case let us assume that the reliabilities of the components are already at their highest level. Then a redesign is necessary and, for this purpose, the 40 principles of TRIZ will be needed to improve the design.

#### *4.2.3 TRIZ (first iteration)*

By examining FR1 we can see that the low-reliability problem comes from the multiphase pump. It is obvious that the redundancy is needed. In fact, TRIZ principle 11 (beforehand cushioning) states "Prepare emergency means to compensate beforehand for the relatively low reliability of an object." Therefore, an additional stand-by pump will be included in the design. For FR2, the only design component is the multiphase meter (MPM). The low-reliability problem can then be solved by using the following TRIZ principles.

*Principle 1 (segmentation)* Suggest the separation of functions of measuring gas, oil, and water (as suggested before by axiomatic design). However, this option will not be suitable because of the nature of the multiphase fluids.

*Principle 5 (merging)* This implies reducing the number of MPMs and increasing the capacity of each MPM. However this solution is not feasible because it has been assumed that the MPMs in use are the biggest available in the market.

*Principle 11 (beforehand cushioning)* In this case, the final solution will be again the use of active redundancy considering that the particular operational context prevents the use of principles 1 and 5.

#### *4.2.4 Axiomatic design (second iteration)*

The application of TRIZ modified the original solution, and then a new iteration was required. However, the need and the FRs in the first iteration remained unchanged, whereas the FRs and DPs in the second design iteration were altered. Specifically, a new FR and its respective DP were included (FR14, DP14) and the DP DP21 was modified. The result of the second iteration using Axiomatic Design is shown in Table 6.

#### *4.2.5 Reliability evaluation (second iteration)*

The reliability of the system must then be recalculated based on the new design. According to the reliability calculation, the new design does comply with the reli-

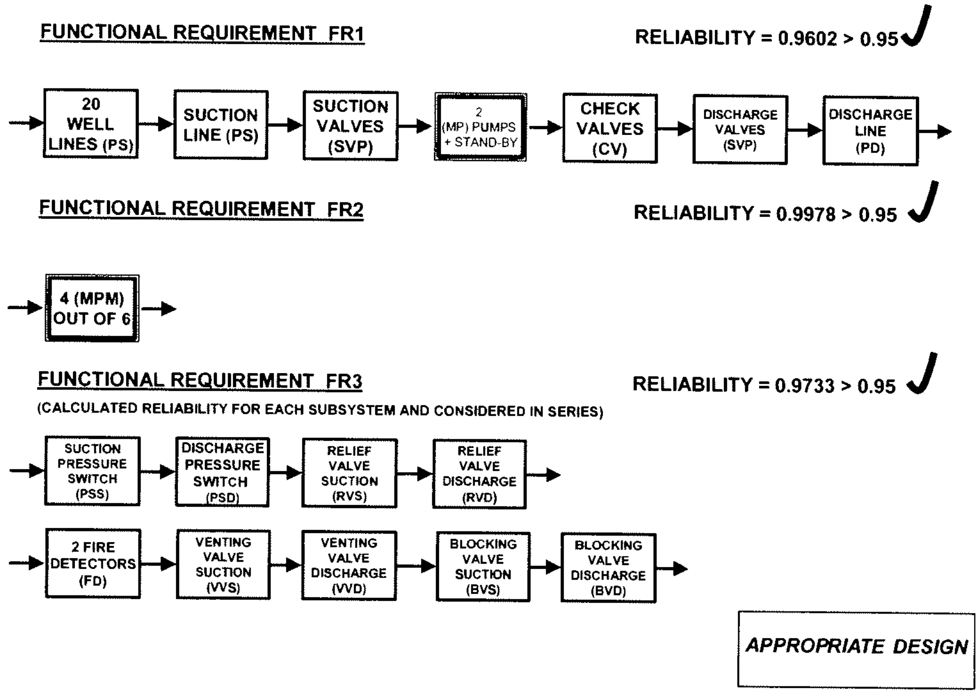



**Fig. 5** Block diagram for the second iteration

**Table 7** Preliminary proposed maintenance plan

| Component | Task | Frequency |
|---|---|---|
| Sectioning valves per well | Test operation | 3 months |
| Operations of sectioning valves per pump | Test operation | 3 months |
| Test for relief valves discharge | Test operation | 3 months |
| Test for relief valves suction | Test operation | 3 months |
| Test venting valve suction | Test operation | 3 months |
| Test venting valve discharge | Test operation | 3 months |
| Automatic valves | Test operation | 3 months |
| Multiphase meters | Test operation | 1 year |
| Multiphase pumps | Vibrational analysis | 1 week |
| | Replacement of mechanical seals | 6 months |
| | Checking screws and gears | 1 year |
| | Checking internal recirculation system | 2 year |
| | Test back-up pump | 1 week |
| Suction pipes | Thickness measurement | 2 years |
| Discharge pipes | Thickness measurement | 2 years |
| Pressure switches suction | Test operation | 3 months |
| Pressure switches discharge | Test operation | 3 months |
| Check valves | Visual inspection | 2 years |
| Fire detectors | Test fire detectors | 3 months |
| Operator for installation | Time expended in installation | 100% |

ability constraint, as shown in Fig. 5. At this point, the system satisfies the customer need and the constraints.

However, to achieve a true reliable design the following questions must be answered:

1. What is needed to keep the reliability of the system at the designed level?
2. How robust is the reliability of the system under different maintenance resources and operational contexts?

To answer the first question, RCM has to be applied.

### 4.2.6 *Reliability centred maintenance*

RCM will allow identifying at early stages the design and resources needed to determine the optimal maintenance and operation plan. It must be emphasized that a team of people with different expertise in operation, maintenance, design, and safety should participate in the RCM analysis. A preliminary maintenance plan to achieve the desired reliability of the installation is summarized in Table 7.

At this level the basic maintenance and operation has been defined based on the expertise of a multidisciplinary design team. However, the designers need to understand and evaluate how robust the system is under different operational contexts. To achieve that, the designers must understand the objective of the system and the variability in the operational context, which is not under the designers' control. To minimize the risk of the system installation, the robust design methodology needs to be applied. Here we assume that the maintenance and operational costs associated with the activities described in Table 7 are equal to or lower than the maximum costs accepted by the designers.Robust design

**Table 8** The factors in robust design analysis

| # | Factor ID | Activity | Factor levels | | |
|---|---|---|---|---|---|
| | | | 1 (RCM) | 2 | 3 |
| Control factor | | | | | |
| 1 | A | Preventive operation of sectioning valves | 3 months | 6 months | |
| 2 | B | Failure finding test of automatic valves | 3 months | 6 months | |
| 3 | C | Failure finding test of electronic switches | 3 months | 6 months | |
| 4 | D | Measurement of pipe thickness | 1 year | 2 years | |
| 5 | E | Visual inspection of check valves | 2 years | 4 years | |
| 6 | F | Fire protection system test | 3 months | 6 months | |
| 7 | G | Replacement of mechanical seals | 6 months | 1 year | |
| 8 | H | Checking screws and gears | 1 year | 2 years | |
| 9 | I | Checking internal recirculation system | 2 years | 3 years | |
| 10 | J | Test back-up pump | 1 week | 2 weeks | |
| 11 | K | Vibrational analysis | 1 week | 2 weeks | |
| 12 | L | Operator for installation | 1 | 0.5 | |
| Noise factor | | | | | |
| 1 | – | % gas | 50% | 80% (design) | 100% |

**Table 9** Experiment design (response MTBF)

| | Control factors | | | | | | | | | | | | | | | Noise | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | A | B | C | D | E | F | G | H | I | J | K | L | | | | 50% | 80% | 100% |
| Exp. No. | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | MTBF1 | MTBF2 | MTBF3 |
| 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | | | | 638.8102 | 5359.8284 | 51.8059 |
| 2 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 2 | 2 | 2 | 2 | 2 | | | | 101.5052 | 118.0237 | 36.2462 |
| 3 | 1 | 1 | 1 | 2 | 2 | 2 | 2 | 1 | 1 | 1 | 1 | 2 | | | | 107.2783 | 125.9016 | 36.9563 |
| 4 | 1 | 1 | 1 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 1 | | | | 70.5674 | 78.1738 | 31.3399 |
| 5 | 1 | 2 | 2 | 1 | 1 | 2 | 2 | 1 | 1 | 2 | 2 | 1 | | | | 94.3032 | 108.3981 | 35.2839 |
| 6 | 1 | 2 | 2 | 1 | 1 | 2 | 2 | 2 | 2 | 1 | 1 | 2 | | | | 77.5898 | 86.8850 | 32.6523 |
| 7 | 1 | 2 | 2 | 2 | 2 | 1 | 1 | 1 | 1 | 2 | 2 | 2 | | | | 95.2437 | 109.6426 | 35.4148 |
| 8 | 1 | 2 | 2 | 2 | 2 | 1 | 1 | 2 | 2 | 1 | 1 | 1 | | | | 106.9910 | 125.5061 | 36.9222 |
| 9 | 2 | 1 | 2 | 1 | 2 | 1 | 2 | 1 | 2 | 1 | 2 | 2 | | | | 73.2177 | 81.4394 | 31.8519 |
| 10 | 2 | 1 | 2 | 1 | 2 | 1 | 2 | 2 | 1 | 2 | 1 | 1 | | | | 101.6830 | 118.2642 | 36.2688 |
| 11 | 2 | 1 | 2 | 2 | 1 | 2 | 1 | 1 | 2 | 1 | 2 | 1 | | | | 98.8514 | 114.4511 | 35.9020 |
| 12 | 2 | 1 | 2 | 2 | 1 | 2 | 1 | 2 | 1 | 2 | 1 | 2 | | | | 102.7774 | 119.7471 | 36.4071 |
| 13 | 2 | 2 | 1 | 1 | 2 | 2 | 1 | 1 | 2 | 2 | 1 | 2 | | | | 89.3710 | 101.9319 | 34.5701 |
| 14 | 2 | 2 | 1 | 1 | 2 | 2 | 1 | 2 | 1 | 1 | 2 | 1 | | | | 115.5181 | 137.4039 | 37.8873 |
| 15 | 2 | 2 | 1 | 2 | 1 | 1 | 2 | 1 | 2 | 2 | 1 | 1 | | | | 88.5424 | 100.8554 | 34.4454 |
| 16 | 2 | 2 | 1 | 2 | 1 | 1 | 2 | 2 | 1 | 1 | 2 | 2 | | | | 81.9782 | 92.4254 | 33.4048 |

As defined in robust design, controllable (control factors), and non-controllable variables (noise factors) must be identified in the design process. In this case, the control factors are maintenance and operational activities and the noise factor is the percentage of gas in the fluid. The percentage of gas is considered as a noise factor because it varies through the useful life of oil wells and affects the overall reliability of the system installation. The response variable is the reliability of the system.

Conventionally, physical experiments need to be conducted in order to apply the robust design approach. However, physical experiments are often technically or economically infeasible in the design stage. Instead of physical experiments, surveys can be conducted to find the system reliability under variations in maintenance and operation. The survey is used to achieve two goals: (1) to verify that the strategy defined by RCM is optimal (using the ANOVA table for the control factors) and (2) to determine the robustness of the system reliability (using the signal/noise ratio analysis).

**Table 10** ANOVA table for ideal conditions

| | *S* | *f* | *V* | *F* |
|---|---|---|---|---|
| SA | 1719927.9 | 1.0 | 1719927.9 | 1.0 |
| SB | 1724481.7 | 1.0 | 1724481.7 | 1.0 |
| SC | 1722794.4 | 1.0 | 1722794.4 | 1.0 |
| SD | 1719685.7 | 1.0 | 1719685.7 | 1.0 |
| SE | 1704559.3 | 1.0 | 1704559.3 | 1.0 |
| SF | 1711578.6 | 1.0 | 1711578.6 | 1.0 |
| SG | 1818581.6 | 1.0 | 1818581.6 | 1.1 |
| SH | 1706954.8 | 1.0 | 1706954.8 | 1.0 |
| SI | 1798512.2 | 1.0 | 1798512.2 | 1.1 |
| SJ | 1735018.5 | 1.0 | 1735018.5 | 1.0 |
| SK | 1754937.1 | 1.0 | 1754937.1 | 1.1 |
| SL | 1760188.7 | 1.0 | 1760188.7 | 1.1 |
| Total | 20877220.5 | 12.0 | 20877220.5 | |
| *e* | 4985499.5 | 3 | 1661833.2 | |

Table 11 ANOVA table for S/N ratio

| Source | *f* | *S* | *V* | *F* (99.5%) |
|---|---|---|---|---|
| A | 1 | 1.02 | 1.02 | 47.53 |
| B | 1 | 1.04 | 1.04 | 48.87 |
| C | 1 | 1.02 | 1.02 | 47.67 |
| D | 1 | 1.00 | 1.00 | 46.95 |
| E | 1 | 0.93 | 0.93 | 43.72 |
| F | 1 | 0.97 | 0.97 | 45.40 |
| G | 1 | 6.16 | 6.16 | 288.41 |
| H | 1 | 0.95 | 0.95 | 44.41 |
| I | 1 | 4.78 | 4.78 | 223.56 |
| J | 1 | 1.26 | 1.26 | 58.85 |
| K | 1 | 2.60 | 2.60 | 121.77 |
| L | 1 | 2.42 | 2.42 | 113.27 |
| Total | 15 | 24.16 | | |
| *e* | 3 | 0.06 | 0.02 | |

In this study, the MTBF is used as the output of the robust design analysis. MTBF can be used for calculating the reliability of the system for any given time and reliability distribution. In designing the "experiment," different levels of the control and noise factors are established based on the design team's experience. In this case, a basic set of maintenance and operation activities are considered as shown in Table 8. Notice that this step can be achieved by using an analytical model to predict the reliability of the system under different circumstances of resource allocation; however, such a model often does not exist at the design stage.

For the listed factors and levels in Table 8, an experimental design matrix $L_{16}(2^{15})$ shown in Table 9 is chosen for this study. The analysis of the control factors using MTBF for ideal conditions is summarized in Table 10. The results indicate that the 12 maintenance and operation activities are important in determining the final MTBF of the system. On the other hand, the S/N analysis shown in Table 11 indicates that under different gas content conditions, only Tasks 7, 9–12 affect the reliability of the system. Therefore, the level of these activities can be adjusted to achieve the best system

Fig. 6 Iterative process for optimal system design

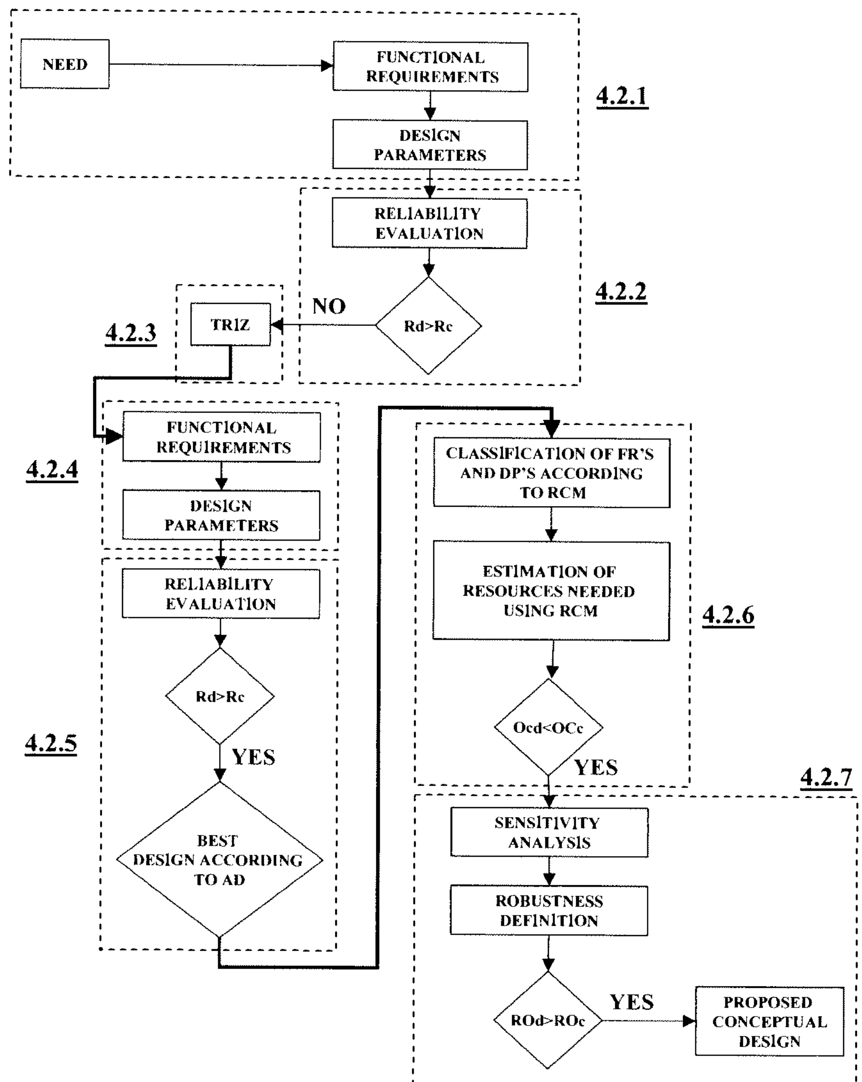
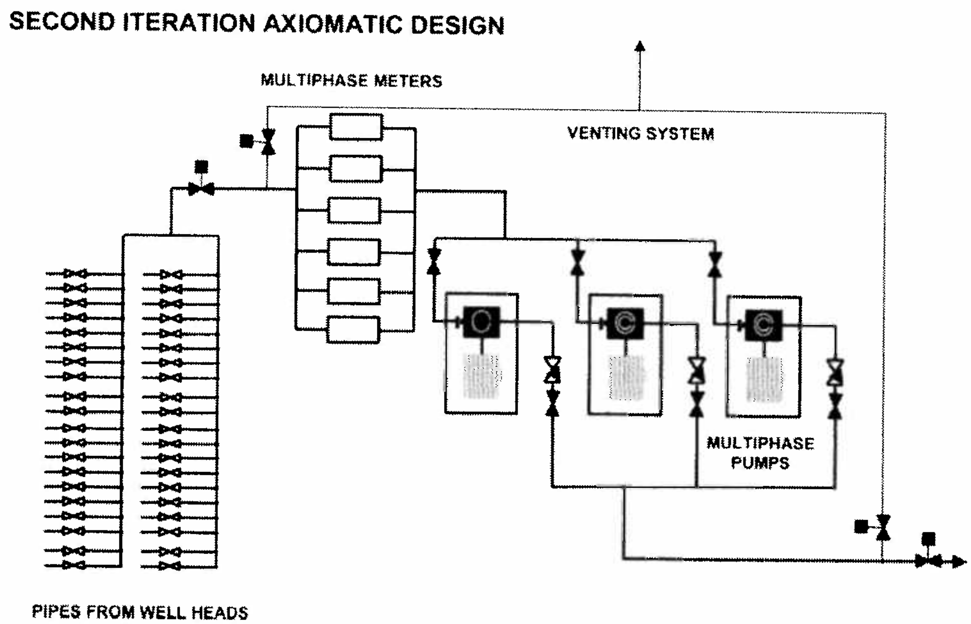


Fig. 7 Final conceptual design




reliability. This result is important for implementing a maintenance and operation strategy that will guarantee the robustness of the system under different gas content conditions.

*4.2.7 Final solution*

After the robust design analysis, the proposed design can satisfy the original needs of the customer, which are identified and transformed into the FRs by the application of axiomatic design. The initial design is refined using TRIZ and the resources needed to keep the system running as designed through its useful life are identified by using RCM. The iterative design process necessary to identify the best design for the particular case presented in this paper is shown in Fig. 6. The steps shown in Fig. 6 correspond to the sub-sections described above and are marked with dotted boxes and the section numbers of this paper. The resulting final design is represented in Fig. 7.

## 5 Discussion

Two major observations can be made from the case study presented above. First, in the application of the data sheet and decision sheet associated with RCM, it is convenient to consider only the total failures because at the conceptual design level there is not enough information on the real operational context to consider the partial failures. Second, in order to realize the benefits of the methodology, it is necessary to make sure that the following conditions are met:

- A design team with the experience in similar installations or products.
- Information about economics and resources for the installation or product.
- Detailed information of the components or sub-systems.
- The reliabilities of the basic components of the system.
- An initial estimation of the maintenance and operational resources in order to keep the reliability of the system as desired.
- Prioritization of maintenance and operational tasks as well as the identification of the consequences of varying the optimal maintenance and operational plan.
- Prediction of the system performance in different scenarios of the noise factors of the system.

## 6 Concluding remarks

A new conceptual design methodology for enhancing the reliability of large systems is proposed in this paper. The integration of axiomatic design, robust design, TRIZ, and RCM yields a hybrid methodology characterized by technical improvements, higher reliability, and customer satisfaction at the minimum cost. The application of the proposed methodology in the conceptual design of a multiphase flow station for oil production indicates that it is feasible to design systems using this new methodology to optimize the system performance under different maintenance and operational scenarios. By bringing the reliability and maintenance considerations early in the conceptual design stage, higher reliability and lower cost in the actual operation and maintenance of these systems can be achieved.

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