Increasing the performance of a Salt Washing Machine through Axiomatic Design

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Abstract. Systems with fewer design parameters (DPs) than functional requirements (FRs) are coupled or cannot achieve all their FRs simultaneously, as per Axiomatic Design’s theorem 1. In that case, production processes have lower productivity and production rate than uncoupled or decoupled designs. This paper reports the upgrading of a salt washing machine concerning its performance, not only on separation of salt from saltwater but also on washed salt production. The machine analysis showed it is a coupled design, with one more functional requirement than the design parameters. A viable enhancement was the addition of one design parameter, which made it possible to control separation and washing independently. This redesign enforced functional independence and allowed increasing the production rate between 20% and 30%. Furthermore, one could perceive increased productivity, quality of the final product, and reduced water and energy consumption.

1. Introduction
The engineering of production systems encompasses two main areas of development: the production process (manufacturing technologies and materials flow and handling) and the production management (flow of information - signals). One must design these two areas to perform according to the stated needs [1]. Furthermore, a good production management requires that the selected conceptual solutions of the production process have a set of independent functional requirements, which is a means to ensure the robustness of solutions.

On the other hand, any manufacturing system aims to maximize productivity [1], as defined by equation (1), according to [2].

\[
\text{Productivity} = \frac{\text{Total added value} - \text{Production costs}}{\text{Total investment}}
\] (1)

Productivity grows by increasing total added value or decreasing either production costs or investment.

Regarding business operations, the added value of a product (or process or service) is brought by its functions, performances, suitability, quality, and price. The added value results from actions in several
areas related to marketing and sales, product development, manufacturing, assembly, quality, and logistics.

As for manufacturing processes, two modes allow obtaining the added value: 1) better use of available time, which lets getting more value per time through the increase of produced quantities; 2) quality of manufacturing operations, which enable reaching the specified functions right at first time, thus making the production time more effective [1].

In a production system where the number of design parameters is less than the number of functional requirements, either a coupled design results or the functional requirements may only be partially satisfied, as per Axiomatic Design’s theorem 1.

In such a situation, the production process has lower productivity than a decoupled design. The decoupled design allows the adjustment of each design parameter to obtain the best achievement for each functional requirement.

This paper shows the successful use of Axiomatic Design (AD) to find the source of the low level of productivity of a salt washing machine and to design an improved solution.

2. Axiomatic Design at a Glance

In the Axiomatic Design (AD) terminology, the depiction of the world of any design object is made in any one of four design domains: the customer, the functional, the physical, and the process domains [2]. These domains are shown in figure 1, and their contents can be described as follows:

“Customer Domain”: contains the Customer Needs (CNs), i.e. the attributes that the customer seeks in the product or in the system that must be designed;

“Functional Domain”: contains the Functional Requirements (FRs) of the design object. In a good design, they are the minimum set of independent requirements that completely describe the functional needs of the design solution, which must be defined in a solution-neutral manner;

“Physical Domain”: contains the Design Parameters (DPs) of the design solution. The DPs are the elements of the design solution that are chosen to satisfy the specified FRs;

“Process Domain”: contains the Process Variables (PVs) that characterize the production process of the design solution, i.e., the variables that allow attaining the specified DPs.

Figure 1. Axiomatic design domains, their contents and relationships (adapted from [3]).

As shown in figure 1, for each pair of adjacent domains, the domain at the left represents "What is required to achieve", or the goals, while the domain at the right represents "How to achieve the goals", or the design solution [2]. That is done by mapping between the goals and the way to achieve them. The extant constraints to this mapping are the bounds for the acceptable solutions and are classified as “input” and “system” constraints [2]. The input constraints are known since the outset of the design process, and the system constraints are found after the outset.
For instance, the mapping between the FRs and DPs is defined by equation (2), the “design equation”, where \{FR\} is the “FR vector”, \{DP\} is the “DP vector”, and \([A]\) is the “design matrix”

\[
\{FR\} = [A] \cdot \{DP\}, \quad A_{ij} = \frac{\partial FR_i}{\partial DP_j}, \quad i = 1..n, \quad j = 1..m
\]

Another unique concept in AD is the hierarchical decomposition through zigzagging between contiguous domains. That advances in a top-bottom way, from the system level and continuing through levels of more detail, as shown in figure 1.

But the fundamental hypothesis of AD is that there are two fundamental principles that govern good design practice [2]:

**The Independence Axiom (the first axiom):**
Maintain the independence of functional requirements.

This means that each FR should be such that adjusting each DP just disturbs the accomplishment of one of the FRs.

**The Minimum Information Axiom (the second axiom):**
Minimize the information content of the design.

The purpose of this axiom is to help in finding out the alternative design solution that has minimum information, which is the one that has the highest probability of achieving the FRs.

The independence axiom and the specific constraints should be applied to the design equation during the decomposition, as to ensure that an “uncoupled” or a “decoupled” design solution is obtained at each level of the design process. Uncoupled and decoupled solutions are characterized by diagonal and triangular design matrices, respectively [2]. Any other shape of the squared design matrix corresponds to a “coupled” design solution that should be avoided. Since the design process does not lead to a unique solution, the information axiom should be used to compare the alternative solutions that were previously found and select the alternative design solution with the highest probability of achieving the FRs [4].

### 3. The Case Study

We aimed at improving the existing salt washing machines in a sea industrial solar saltern. According to AD, one has to carefully define the design's main goals at the onset of the process. The design process can proceed only after stating those goals clearly [5].

#### 3.1. The industrial process of reclaiming and washing salt

In the industrial process of sea salt harvest formed in traditional crystallizer ponds, a mixture of salt crystals and clay is obtained, with the clay particles coming from the bottom of those ponds. Figure 2 shows some overall aspects of the industrial process of sea salt harvesting.

![Figure 2. The industrial sea salt harvesting process.](image)

Therefore, there is the need to separate the clay particulate from the salt crystals.
The process of forming crystalline structures warrants there is no clay inside the salt crystals. The typical way to separate the salt from the clay is to dilute the mixture through mechanical agitation in a liquid phase that does not dissolve the particulate. The liquid phase commonly used is an aqueous solution saturated with salt, called brine. Brine cannot dissolve more salt, thus keeping the balance between the salt that will likely dissolve and the salt that recrystallizes. Slow-speed controlled precipitation enables separation.

Figure 3 shortly depicts the salt washing process through shaking. Fast shaking enables diluting the mixture, while slow agitation allows separating salt crystals from clay particulate.

The machines traditionally used to perform salt washing are made up of a tank where the salt with clay is diluted in salt-saturated brine. A screw conveyor shakes the mixture to disperse the clay and the salt crystals in the brine. The screw conveyor rotation motion is also meant to separate the salt from the clay through separate drainage. The salt is removed from the washing tank through the underflow outlet at the higher side of the tank, while the brine with clay leaves the tank through overflow outlet located at the lower side of the tank. Some examples of existing salt washing machines are shown in figure 4.

3.2. Axiomatic Design analysis
Figure 5 shows the main customer need: to separate the clay from the valuable washed salt.
Figure 5. Customer needs to separate the clay from the salt – Customer Domain.

Therefore, the main functional requirements of the salt washing process are the following:

At the first hierarchical level, we have:
FR$_1$ – Wash salt

At the second hierarchical level, we have:
FR$_{2.1}$ – Accept mixture (salt with clay)
FR$_{2.2}$ – Dilute mixture
FR$_{2.3}$ – Extract clay
FR$_{2.4}$ – Segregate salt

At the third hierarchical level, we have:
FR$_{2.1.1}$ – Collect washed salt
FR$_{2.1.2}$ – Collect clay

As system constraint, we do not want to dissolve the salt.
Schematically, these operations (FRs) can be represented as shown in Figure 6.

Figure 6. Functional requirements to separate the clay from the salt – Functional Domain.

The perceived main design parameters for the case of traditional salt washing machines are the following:

At the first hierarchical level, we have:
DP$_1$ – Salt Washing Machine

At the second hierarchical level, we have:
DP$_{2.1}$ – Washing Tank
DP$_{2.2}$ – Brine
DP$_{2.3}$ – Screw conveyor

At the third hierarchical level, we have:
DP$_{2.1.1}$ – Tank’s underflow outlet
DP$_{2.1.2}$ – Tank’s overflow outlet
Figure 7 represents the solutions (DPs) to perform the above-said actions (FRs).

Figure 7. Design parameters and functional requirements of a traditional salt washing machine.

Figure 8 shows the functions as they occur along the salt washing machine.

Figure 8. Design parameters and functional requirements along a traditional salt washing machine.

Figure 9 displays a traditional salt washing machine.

Figure 9. Design parameters of a salt washing machine (Physical Domain).
In traditional washing machines, the same DP, the rotating shaft, implements two FRs. These two functional requirements exhibit a coupling: for extracting clay, shaking the mixture fast is required, while slow shaking allows for segregating salt. That functional coupling forbids physical integration.

As one can see in equation (3), the design matrix for the second hierarchical level, has more FRs than DPs, so that the design matrix is not square

\[
\begin{bmatrix}
FR_{2.1} \\
FR_{2.2} \\
FR_{2.3} \\
FR_{2.4}
\end{bmatrix} =
\begin{bmatrix}
\times & 0 & 0 \\
0 & \times & 0 \\
0 & \times & \times \\
\end{bmatrix}
\begin{bmatrix}
DP_{2.1} \\
DP_{2.2} \\
DP_{2.3}
\end{bmatrix}
\]

The 3rd level FRs are accomplished independently and are not necessary for the following discussion. AD’s theorem 1 (Coupling due to insufficient number of DPs) states, “When the number of DPs is less than the number of FRs, either a coupled design results or the FRs cannot be satisfied.” [2].

Therefore, the traditional salt washing machines are coupled designs since the number of DPs is smaller than the number of FRs at the second decomposition level. Their functional requirements are never fully satisfied because one cannot increase the shaft speed sufficiently to warrant effective clay extracting, and the shaft speed cannot be as slow as required to avoid prejudicing salt segregation.

We tried other solutions to improve shaking, for example, by adding transverse fins on the propeller blade to increase the turbulence of the mixture within the clay extraction section of the tank while keeping the conveyor speed low to ensure salt segregation. Another way to keep the conveyor's speed low was to apply compressed air jets inside the extraction section to create a jacuzzi effect, although the improvements were not significant.

3.3. The new design

In the end, the adopted solution was to divide the screw conveyor into two sections with independent rotation movement: a high-speed conveyor in the extraction section of the tank, and a low-speed conveyor in the segregation section. Figure 10 shows the design parameters for a two-screw conveyor salt washing machine.

![Figure 10](image-url)
At the second hierarchical level, the design parameters of the new design are as follows:

- DP$_{2.1}$ – Washing Tank
- DP$_{2.2}$ – Brine
- DP$_{2.3}$ – Screw conveyor 1
- DP$_{2.4}$ – Screw conveyor 2

The salt and the clay find their way from conveyor section 1 to conveyor section 2 by themselves. The hierarchical zigzag decomposition is shown in figure 11.

![Figure 11](image)

**Figure 11.** The zigzag path of the hierarchical decomposition of a split screw salt washing machine.

As one can see in equation (4), the matrix became square, and the design became decoupled.

\[
\begin{bmatrix}
\text{FR}_2.1 \\
\text{FR}_2.2 \\
\text{FR}_2.3 \\
\text{FR}_2.4
\end{bmatrix} =
\begin{bmatrix}
0 \\
0 \\
0 \\
0
\end{bmatrix}
\begin{bmatrix}
\text{DP}_2.1 \\
\text{DP}_2.2 \\
\text{DP}_2.3 \\
\text{DP}_2.4
\end{bmatrix}
\]

*Equation (4)*

### 4. Results

The proposed solution consists of the addition of one DP to allow controlling the separation and the washing functions in a decoupled way. The final configuration for the new salt washing machine encompasses the division of the screw conveyor into two conveyors with independent rotation speeds, allowing a higher rotation speed in the clay extraction section and a lower velocity in the salt segregation section.

Using the glossary of AD, FR$_{2.3}$ and FR$_{2.4}$ become decoupled and are achieved by sequentially adjusting the speeds of the two screw conveyors. The new solution allowed improving the separation and segregation functions efficiencies while increasing the washing speed by 20% to 30%. Furthermore, the process productivity and the final product’s quality improved in a meaningful manner. At last, the same amount of produced washed salt requires less water and energy.

### 5. Conclusions

In traditional washing machines, the same DP (the screw conveyor) touches two functional requirements so that the number of DPs is smaller than the number of FRs. Following AD's Theorem 1, such peculiarity characterizes coupled designs. The analysis of the design matrix in equation (3) reveals this condition, which usually indicates the poor performance of the corresponding design solution.
The new design resulted from equation (3), to which a new DP was added to accomplish a decoupled design solution. The new DP is a second screw conveyor, which allows adjusting each DP independently to obtain the best fulfillment for each FR. The new design solution reaches:

- improved productivity.
- reduced consumption of brine, water, and energy by about 30%.
- increased production speed by between 20% and 30%.
- increased perceived quality level of the final product.

Axiomatic Design theory enabled analysis and finding the source of the problem, allowing also redesigning a more efficient solution that increases productivity and improves environmental sustainability.

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