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Redesign of the SureTrack grader transfer bin using Axiomatic Design

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Abstract

The Marel SureTrack grader is equipped with transfer bins for grading of predetermined masses of fish. The bins are expensive to manufacture (≈€1000) and cracks in the weld joining the sides of the bin have been observed during operation. In this paper, a bin redesigned using Axiomatic Design theory is presented. Axiomatic parameters are devised from reverse engineering of the original bin and attributes seen as desirable to the client. The strength of the redesigned bin and its welds was estimated using finite element analysis. CAD Software was used to estimate the manufacturing cost of the bin once all costing parameters had been defined. For comparison purposes analysis were performed on models of the original design and the redesigned bin. The cost of manufacturing the redesigned bin is 12% less than the cost of manufacturing the SureTrack bin and 47% stronger for the load case analyzed.

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Keywords: Axiomatic Design; fish; food processing

1. Introduction

Marel hf. is one of Iceland's leading high technology companies: one of the countries largest manufacturing companies and a large software company rolled into one. One of Marel's popular products is known as the SureTrack grader. The primary function of a grader is to selectively create batches of fish of the same quality level at a predefined weight. The SureTrack grader is often used in salmon processing by Marel's customers to sort and batch fish for sale. The SureTrack utilizes open bins which are loaded from the top and emptied by a lever mechanism which releases the bin bottoms. These bins are driven by a pair of drive chains on an elliptical path.

Although the SureTrack grader has been successful, its use has not been problem-free. In addition to being very expensive to manufacture (≈€1000), SureTrack transfer bins sometimes develop fatigue fractures along a weld line in the main structural assembly of the bin. A Master's Thesis project was undertaken with the objective of ascertaining whether the design of the bin could be improved upon by employing systematic design tools, namely Axiomatic Design [1].

Axiomatic Design is a design framework developed by Nam P. Suh which employs domains, mappings between the domains, two axioms, and decomposition by zigzagging between the domains [2,3].

The following sections explain the process used for the design of an improved bin. We first provide an analysis of the original bin's design. The next section focuses on the application of AD in the design of the new bin. A subsequent section contains an overview of the redesigned bin and the analysis performed. We close with the conclusions drawn from the project.

2. Analyzing the original bin

The bins of the SureTrack grader serve the purpose of transporting the fish between the infeed and outfeed of the grader. The bins are designed to be able to transport a batch of fish weighing up to 25 kg. The bin is made entirely out of 1.4301 stainless steel except for the support wheel assemblies and bushings in the discharge mechanism.

A material choice such as this steel and surface finish is constrained by food sanitation practice and regulation. All materials must minimize adhesion of food and be compatible with aggressive cleaning agents in a high-pressure spray [4].

The SureTrack bin can functionally be split into three separate elements: main weldment, discharge system, and support system. The main weldment is the primary element onto which the other two are attached. These elements of the SureTrack bin are shown in Figure 2.

As noted above, cracking at the weld line between the long sides and the gable ends of the main weldment has been observed. Marel's engineers theorized that the recurring impact from the dropping of the fish into the bin might be causing fa-

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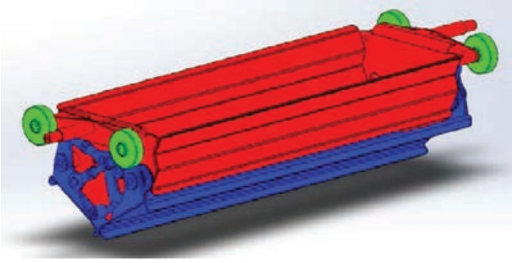

Fig. 1. The SureTrack bin elements: main weldment (red), support system (green), and discharge system (blue).

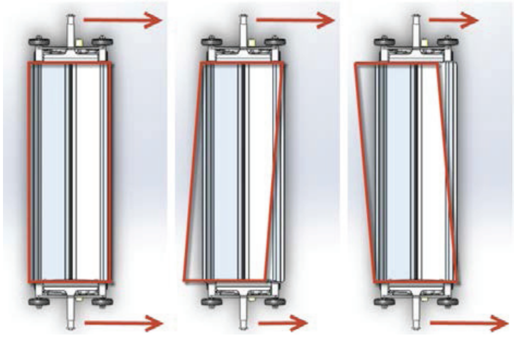

Fig. 2. If drive forces are equal, the square shape of the main weldment is preserved. Uneven forces cause parallelogram deformations.

tigue cracking in the weld line. The impact might be contributing to the cracking, but given the orientation of the joint relative to the loading, this seems unlikely. It is more likely that uneven force from the drive system might be inducing parallelogram motion within the main weldment of the SureTrack transfer bin. This possibility is pictured in Figure 2.

This parallelogram motion of the main weldment is presumably only slight, where the difference between the drive points is only a few millimeters or less. However, due to the large span of the SureTrack bin, this movement is amplified to fractions of a degree on the welded joint. While this movement is only slight, the motion may become frequent and cyclic during the operation of the SureTrack grader, resulting in significant fatigue loading. The cause of this imbalance may originate from jerky motion in the drive chain caused by an accumulation of debris during the operation of the grader, slight variances in the build of the grader, or excessive wear. Another possibility is that the alignment of the cams that operate the discharge mechanism of the bins is off by a small amount causing the cam to come into contact with the operating lever of the discharge mechanism a before the opposite cam contacts.

3. Bin redesign using the AD process

As stated earlier the current design of the SureTrack bin is considered expensive and is vulnerable to fatigue cracking in its current deployment. These two facts along with the necessary considerations of what the bin is supposed to accomplish to can be used to list the following design considerations:

- Design a cost-effective variant of the SureTrack bin.
- Insure full discharge of the bin.
- Insure the system can be discharged in any straight running part of the system.
- Prevent accidental discharge of the bin.
- Reduce the risk of fatigue cracking due to possible skewing of the bin.

Using this information it's possible to realize the customer's need (CN): we know that the customer wants a stronger bin at a lower price or a less expensive but equally strong bin. The formal statement of the customer's need would be:

> **$\mathbf{CN}_0$** A transfer bin for whole salmon, compatible with the SureTrack grader, cheaper and less prone to cracking due to skewing. The bin should be adaptable to a pure transfer task and be able to discharge anywhere along its path without accidental discharge.

With the CNs formalized the designer's task is to map the CNs to appropriate Functional Requirements (FR) in the Functional Domain.

It is clearly evident from the CN that the basic requirement of the bin is to transfer whole fish, any other demands made of the bin are secondary but important enough to determine if the design is usable or not. The meaning of the previous statement is that a perfect bin with an extremely low production cost and nearly unlimited strength is unusable if the bin is not able to transfer the product. The statement of the base level FR thus becomes:

> **$\mathbf{FR}_0$** Contain 25 kg of fish on SureTrack conveyor until release is triggered.

The designer's task at this point is to map the information in the Functional Domain to the Physical domain and in doing so, defining how the Functional Requirements shall be realized. The information used in the formulation of the base level Design Parameter is drawn from both previous statements of the CNs and FRs and from the knowledge gleaned from the current design. The statement of the base level Design Parameter becomes:

> **$\mathbf{DP}_0$** Gable-reinforced stainless-steel locking bin with bi-directional discharge

3.1. *Refining the requirements*

Having established the base level FR and DP pair, the decomposition of this base level into lower level pairs can commence. The base level FR_0: "Contain 25 kg of fish on SureTrack conveyor until release is triggered" has a natural decomposition of containing the product while it is in the bin, moving the product, and discharging the product once it's been moved to the appropriate location. The FRs are then mapped to DPs: the product is contained within the main weldment of the bin, the product is discharged by the discharge system and the product and bin are moved by the support system.

As should be clear, the process of developing these requirements follows Axiomatic Design standard practice: top-to-bottom, zig-zagging at each level before decomposing further.

This results in the top level FRs and associated DPs listed in Table 1.

Table 1. Top level FR-DP pair.

ID	Functional Requirement	Design Parameter
1	Contain product	Main weldment
2	Move product	Support system
3	Discharge product	Discharge system

Table 2. Top level Constraints.

ID	Constraint
1	Center distance of wheels shall be 940 mm.
2	The support pin shall have a diameter of 20 mm where it meets the drive chain and be appropriately sized for a chain center to center span of 1099 mm.
3	Maximum width of the bin, excluding the support system shall not exceed 950 mm.

This set of FRs and DPs resulted in the decoupled design matrix in Eq. 1. This indicates that the order in which the DP values/solutions are chosen is important. This was taken into account during the development of the design. FR_1 "Contain product" is coupled to DP_1 'Main weldment" and DP_3 "Discharge system" because we were unable to completely separate the containment and release mechanism.

As the geometries were chosen, the Information Axiom was applied to make sure that the FRs were met over a large variety product batch sizes.

$$\begin{Bmatrix} FR_1 \\ FR_2 \\ FR_3 \end{Bmatrix} = \begin{bmatrix} X & 0 & X \\ 0 & X & 0 \\ 0 & 0 & X \end{bmatrix} \begin{Bmatrix} DP_1 \\ DP_2 \\ DP_3 \end{Bmatrix} \quad (1)$$

The Constraints in Table 2 focus on compatibility with the SureTrack grader.

For $FR_{1.1}$, the first Constraint is most applicable. The width of the bin is limited by the fact that it must fit inside the frame of the SureTrack grader.

With the top level FRs and DPs, as well as the Constraints obtained, the decomposition can be continued to the next level with the further refinement of the first DP. For the first FR, the bin needs to contain not only a single fish but on the outfeed side of the SureTrack grader it needs to be able to carry a batch of fish up to 12.5 kg. Additionally, the main weldment (DP_1) needs to provide mounting for the support and discharge systems, so those become FR_2 and FR_3, respectively. Lastly, the risk of the bin failing due to fatigue shall be decreased. Using this information, Table 3 is populated.

Table 3. FR_1 decomposition.

ID	Functional Requirement	Design Parameter
1.1	Contain product batch	Volume ≥ 25 L
1.2	Support the support system	Removable support pin
1.3	Support the discharge system	Central bearing pin

Table 4. FR_2 decomposition.

ID	Functional Requirement	Design Parameter
1.4	Increase skewing resistance	Joint geometry changes to reduce joint stress
2.1	Rotate freely during vertical motion	Support pin
2.2	Maintain constant orientation	Moment countering wheels during horizontal motion

Table 5. FR_3 decomposition.

ID	Functional Requirement	Design Parameter
3.1	Discharge only where specified	Locking mechanism
3.2	Discharge while traveling horizontally	Vertical actuation of discharge system
3.3	Promote full discharge	Discharge area

The decomposition of the FRs continues with a further examination of FR_2. The transfer bin should maintain its orientation no matter in which direction it is traveling. A force should act on the bin to open it during its horizontal travel. Therefore, it makes sense to split this into two separate FRs as per Table 4. In order to allow for the bin to rotate freely during the portions of vertical travel of the track, the bin must be able to rotate freely; the axis must have an offset to prevent the bin from tipping over. For the horizontal portion of travel, the bin must be able to travel without any rotation, even during the contact with the actuation mechanism of the discharge system. This force can be countered with moment negating wheels. The support pin of $DP_{2.1}$ is restricted by Constraint 2 in Table 2 as the support pin of the redesigned in must appropriately interface with the drive chain of the SureTrack grader.

The location and moment countering wheels of $DP_{2.2}$ are limited by Constraint 3 in Table 2, as the wheels must fit the track of the SureTrack grader.

The third top-level FR is decomposed in a manner identical to the previous FRs. It is clear the product should only be discharged when it's specifically called for, therefore, we need to employ some sort of locking mechanism. Secondly, for the sake of a transport system, we want it to be possible to discharge the contents of the bin irrespective of the traveling direction, i.e. whether it's traveling on the upper tier or the lower tier. Therefore, we specify that the actuation of the discharge system should be in the vertical direction. Lastly, we want to ensure a full discharge of the bin which requires a sufficient opening of the discharge system.

The second-level design matrix can be found in Equation 2.

In order to fulfill the FRs derived in the previous section while innovating over the current SureTrack bins design, it's necessary to review each FR-DP pair and analyze how the design can be optimized.

$$\begin{Bmatrix} FR_{1.1} \\ FR_{1.2} \\ FR_{1.3} \\ FR_{1.4} \\ FR_{2.1} \\ FR_{2.2} \\ FR_{3.1} \\ FR_{3.2} \\ FR_{3.3} \end{Bmatrix} = \begin{bmatrix} X & X & 0 & 0 & 0 & 0 & X & 0 & 0 \\ 0 & X & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & X & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & X & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & X & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & X & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & X & X & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & X & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & X \end{bmatrix} \begin{Bmatrix} DP_{1.1} \\ DP_{1.2} \\ DP_{1.3} \\ DP_{1.4} \\ DP_{2.1} \\ DP_{2.2} \\ DP_{3.1} \\ DP_{3.2} \\ DP_{3.3} \end{Bmatrix} \quad (2)$$

3.2. *Contain Product (FR_1)*

The DP associated with the $FR_{1.1}$ "Contain product batch" is $DP_{1.1}$ "Volume," as the bin must contain the prescribed batch of product. The standard container used is a 50 L Styrofoam (closed cell Polystyrene) box designed to hold 25 kg. The volume of the original SureTrack bin is just under 31 L, providing enough volume to fill the box in two batches. The redesigned bin must also meet this requirement, indicating a minimum volume of 25 L.

The system of parts supporting the bin need to be fastened onto the main weldment of the bin, hence the statement of the $FR_{1.2}$ "Interface with support system" and it's respective $DP_{1.2}$ "Removable support pin". In the case of the SureTrack transfer bin, the support system is a support pin that interfaces with the chain drive of the SureTrack grader and wheels to prevent the bin from tipping when the force of the discharge actuation mechanism is applied to the bin. As the redesigned bin is to be used with the SureTrack grader, the part interfacing with the grader can not be changed, but the way they interface with the grader can. Having the support pin removable would allow for the possibility of the discharge system utilizing the support pin as a bearing pin and therefore negating the need for welding additional bearing mounts to the main weldment.

The discharge system needs to be mounted to the bin's main weldment as indicated with the $FR_{1.3}$ "Interface with discharge system" and its associated $DP_{1.3}$ "Central bearing pin". As the support pin that interfaces with the chain drive of the SureTrack grader must be centrally located on the gable end of the bin, it's ideally suited for providing the rotational axis that the doors of the discharge system rotate about. For this implementation to be feasible, the support pin must also be removable.

3.3. *Move product (FR_2)*

The DP associated with the $FR_{2.1}$ "Increase skewing resistance" is $FR_{2.1}$"Joint geometry changes to reduce joint stress". This stiffening can be realized in a number of design features, including an extended weld area, stiffeners or outriggers, or a joint with a higher inertia moment.

The weld joining the gable ends and the long sides of the SureTrack bin is "s" shaped, presumably to increase the strength of the long side itself and strengthen the welded joint. The total length of the joint is 109 mm. The maximum transverse displacement of the welded joint is 26 mm.

The bin must be prevented from rotating during horizontal travel as per $FR_{2.2}$. Conversely, it must bee free to rotate during non-horizontal travel to avoid tipping as the drive chain traverses its path around the SureTrack grader. This rotation is best implemented where the support pin meets the drive system of the grader, as this calls for no changes to be made to the grader ($C_{2.1}$). Therefore, the end of the support pin mating with the drive system needs to stay unchanged. This does not interfere with the proposed dual function of the support pin described in Section 3.2, as the end of the support pin that mates with the bin itself can be adapted to this task. The DP associated with the $FR_{2.3}$ "Constant orientation during horizontal motion" is $DP_{2.3}$ "Moment countering wheels". The reason that this is important concerns both the charging and discharging of the bin. Any rotational motion has to be prevented during these actions. Due to the limitation imposed by the backward compatibility of the redesigned bin with the SureTrack grader, this method was used for the redesigned bin as well.

3.4. *Discharge Product (FR_3)*

To fulfill the $FR_{3.1}$ "Discharge only where specified" it is necessary to ensure that the bin is locked and not just closed, resulting in $DP_{3.1}$ "Locking mechanism". The locking mechanism is, however, dependent on the design of the discharge mechanism itself.

Technically, this could be achieved by having a two-step activation of the discharge system. With the first step, or amount of actuation, the lock would be disengaged. By increasing the level of actuation to the second step, the discharge would be activated. For this purpose, a sliding joint could be employed. integration of the lock in the discharge mechanism as part of actuation might result in considerable savings due to the consolidation of parts.

In order to fulfill the $FR_{3.2}$ "Discharge while traveling horizontally", $DP_{3.2}$ "Vertical actuation of discharge system" was defined. With the actuation mechanism in the vertical direction, the discharging process can be independent of the traveling direction of the bin. To discharge the bin, the discharge actuation mechanism on the SureTrack grader would have to be designed focusing on symmetry or reversibility to maintain compatibility with bi-directional discharge.

Although the DP states that the actuation direction of the discharge system should be vertical, the chosen implementation uses upward movement. The task of reversing the force within the discharge mechanism is unneeded with this concept: the bin will close by its own weight after the discharge is complete.

The DP associated with the $FR_{3.3}$ "Insure full discharge" is $DP_{3.3}$ "Discharge area", meaning that the discharge area of the bin must be large enough to ensure a full discharge in a sufficiently short amount of time when called for. The SureTrack bins construction has a discharge area of $0.18\,m^2$ which is nearly identical to the input area of the bin. The discharge area of the SureTrack bin has proven to be sufficient to provide an accurately directed and complete discharge. Ideally, the redesigned bin should have an equal ejection area to the one of the SureTrack bin but a reduction down to 60% should still be sufficient. The need for increased skewing resistance which necessitates dropping the near vertical seam between the bins gable ends and long sides in favor of a joint offering more inertia moment. This change is able to still provide an aperture of 60% of the original.

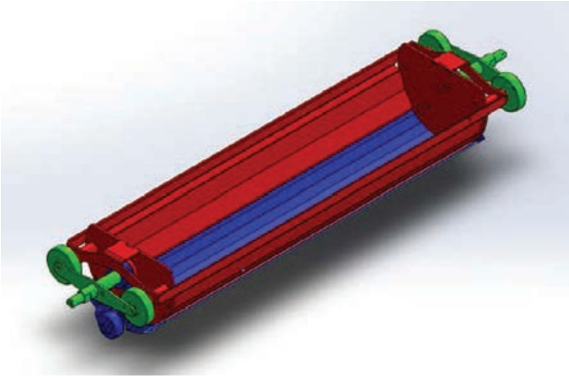

Fig. 3. The Redesigned bin: main weldment (red), support system (green) and discharge system (blue).

3.5. Redesigned bin summary

The basic theory of the design was that by making the product container of the main weldment round, increased stiffness in the joint between the gable ends and the long sides of the bin would be achieved from a longer, more favorably shaped joint. Outriggers added to the support system would further assist in providing increased joint stiffness. By making the section profile of the bin round, the movement of the discharge system could be rotational, thus enabling the use of the support pin as the rotational axis.

For a discharge system of a semi-round profile, the locking, and actuation system employed by the original SureTrack bin were impractical. A new discharge system was devised where an upward force from a cam-based discharge actuation mechanism located on the SureTrack grader would trigger the discharge mechanism. Additionally, the discharge system was refined to be positively locked unless activated. The release of the lock is triggered with the same motion as the actuation of the discharge system. As the redesigned bin must be a drop-in replacement for the SureTrack bin in current machinery, it bears significant geometric similarities to the SureTrack bin.

We believe this is a lower-information design because it is able to function for longer and is less likely to drop its load prematurely.

This new design can be seen in Figure 3.5.

4. Analysis of the redesigned bin

For the redesign of the bin to considered successful, Functional Requirements need validation using the Design Parameters chosen for the design. In addition, the performance of the redesigned bin should be superior to the SureTrack bin in the relevant categories. The bin concept was developed in SolidWorks CAD, which was also used to simulate its specifications and performance. The following is a review of how the redesigned bin meets the FRs.

4.1. Contain Product (FR_1)

$FR_{1.1}$ established that the bin should be capable of containing a batch of product. The DP associated was further refined in Section 3.2 to state that the volume of the redesigned bin should be at least 25 L. The volume of the redesigned bin is 25.2 L. Therefore, the design goal of containing a product batch was achieved.

$FR_{1.2}$ and its respective DP established that the bin should have mounting points for the support system. The redesigned bin is equipped with two welded nuts on either gable end to which the moment countering wheels of the support system are attached. Another weld-nut is provided for the support pin to be screwed into the main weldment on either gable end. Therefore, the design goal of providing mounting points for the support system was achieved.

$FR_{1.3}$ and its respective DP established that the bin should have mounting points for the discharge system. During further refinement of this mounting, the design goal of using the support pin as an attachment and rotational point for the discharge system was expressed. In the final design of the redesigned bin, the support system rotates about the support pin in bushings. Additionally, a welded nut is provided for a guide bar of the discharge system on the main weldment gable end. Therefore, the design goal of using the support pin as a mount point for the discharge system, as well as providing overall connection of the discharge system to the main weldment was achieved.

4.2. Move product (FR_2)

$FR_{2.1}$ and the associated DP called for decreasing the risk of a fatigue failure by reducing the stress in the joint. This can be accomplished by changing the geometry of the joint between the long side and the gable end and adding a stiffener. Both design elements were incorporated. Therefore, the design goal of increase the skewing resistance of the bin was achieved.

During the further breakdown of the $FR_{2.2}$ “rotate freely during vertical motion”, it became clear that due to the nature of the connection of the SureTrack bin to the SureTrack grader, it would be necessary to maintain the current design of the support pin end. The geometry of the support pin end connecting to the drive system of the SureTrack grader was maintained and the pin is free to rotate where it connects with the drive system. Therefore, the design goal of being free to rotate during vertical motion was achieved.

According to $FR_{2.3}$ the activation of the discharge mechanism would produce a moment about the support pin of the bin. This moment would cause the bin to rotate unless countered. To counter this effect moment countering wheels were specified in Section 3.3. Moment countering wheels are a part of the design of the bin and therefore the design goal of maintaining constant orientation during horizontal motion was achieved.

4.3. Discharge Product (FR_3)

In order to fulfill $FR_{2.4}$ that stated that the bin should only discharge when intended, the DP called for a locking system to keep the bin locked during all non-discharging functions. A locking system was designed that can only open with a specific vertical motion of the locking mechanism. Therefore, the design goal of discharging only when intended was achieved.

As one of the customers goals with the redesign of the bin was to have the possibility of using the bin in a pure transfer system, it must be possible to discharge the bin irrespective of its traveling direction ($FR_{3.1}$). A discharge system was designed that is fully symmetrical with respect to the direction it is activated. Therefore, the design goal of discharging in either horizontal direction was achieved.

The design goal ($FR_{3.2}$) for the discharge area of the redesigned bin was set at 60% of the SureTrack bins discharge area which is 0.108 m. The actual discharge area of the redesigned bin is 0.125 m. Therefore, the design goal of promoting full discharge was achieved.

5. Conclusion

The Axiomatic Design framework proved to be an excellent method with which to systematically approach the redesign of the SureTrack bin. AD allowed for addressing each important design parameter before any implementation took place, minimizing the possibility of having to repeatedly address features as design changes were made. Defining acceptable parameters for each functional value beforehand was helpful in order to ascertain when then the design was acceptable.

Designing the bin in a CAD system such as was employed in the design of the SureTrack bin and the redesigned bin proves invaluable when it comes to estimating and evaluating the design. Using the SolidWorks CAD suite, it was possible to evaluate the strength of the redesigned bin versus the SureTrack bin, as well as evaluate the manufacturing cost of each bin.

One of the primary factors for redesigning the bin was the cracking experienced in the seams between the long sides and gable ends of the bin. It was theorized that the cracking could be due to loads generated by the SureTrack grader causing the bin to skew. A Finite Element Analysis (FEA) simulation was run to estimate the improvement in the redesigned bins improved ability to counter this skewing. The results from the analysis were promising: the skewing strength of the bin is improved 47.2% over the SureTrack bin. The sheet thickness and weld parameters in the redesigned bin are equal to those in the SureTrack bin indicating the improvement is due to the geometry of the joint between the long sides and gable ends.

According to the fatigue analysis tools, the base material of neither bin appear to be susceptible to fatigue failure. The tools available in SolidWorks do not perform fatigue analysis for the weld bead itself but the parallel shear stresses recorded in the weld bead decreased by 64%. The joint strength has been increased substantially and the potential life of the part has been increased accordingly.

A second motivation for the improvement of the bin was the cost of manufacture. The SureTrack bin is considered quite expensive to manufacture (≈€1000). Any significant decrease in cost would heavily impact the overall cost of the standard 120-bin SureTrack grader configuration.

An analysis performed on manufacturing resources required to produce each design yielded interesting results as indicated in Table 5.

The redesigned bin makes more use of manufacturing methods that are cheaper, by decreasing the need for turning, milling, and welding necessary. By focusing on using less expensive manufacturing techniques as well as eliminating the need for the expensive rod ends, the cost was decreased as shown by the Costing add-on for SolidWorks. According to the costing analysis, the manufacturing cost of the Redesigned bin was decreased by 1315.19 ISK compared to the SureTrack bin, from 38748.6 ISK to 37433.41 ISK. This amounts to a cost decrease of around 3,4 %. However, this is not the complete picture; the costing analysis was not configured to consider the cost of the rod ends of the SureTrack bin discharge system. Adjusting for the costs of the rod ends causes the savings to become considerable. When the cost of the rod ends is added to the cost of the SureTrack bin, the estimated manufacturing cost totals 42748.6 ISK and the decrease in cost using the redesigned bin becomes 12.4%.

Table 6. Difference in manufacturing metrics between the SureTrack bin and the Redesigned bin.

Element	Diff. from SureTrack bin
Sheet metal, cutting length	15.2%
Sheet metal, number of bent parts	66.6%
Sheet metal, number of bends	87.5%
Turned and milled parts	-26.6%
Welding, number of welds	5.9%
Welding, length of welds	-20.7%

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