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Emergent Design Failure: Lurking Dangers of Regression-Based Design

Introduction and Background

The objective of this capstone project was to apply design theory principles in an analysis of my completed senior ship design capstone project from *NA 470: Foundations of Ship Design* during the Fall 2020 semester, the *M/V Sisukas*. The project involved learning about the principles of Emergent Design Failure, identifying areas of difficulty during the design of the *Sisukas* which had resulted in Emergent Design Failure, and exploring and mapping the design decisions made during the ship design which led to the Emergent Design Failure.

Figure 1. 3D rendering of the *M/V Sisukas*, a 3,500 TEU container ship.

Design is highly path-dependent, as design decisions are made, the flexibility of the design decreases and available options become more restricted. However, the least information is available to inform design decisions at the earliest stages of design when decisions will have the most extensive impact on the rest of the design process.

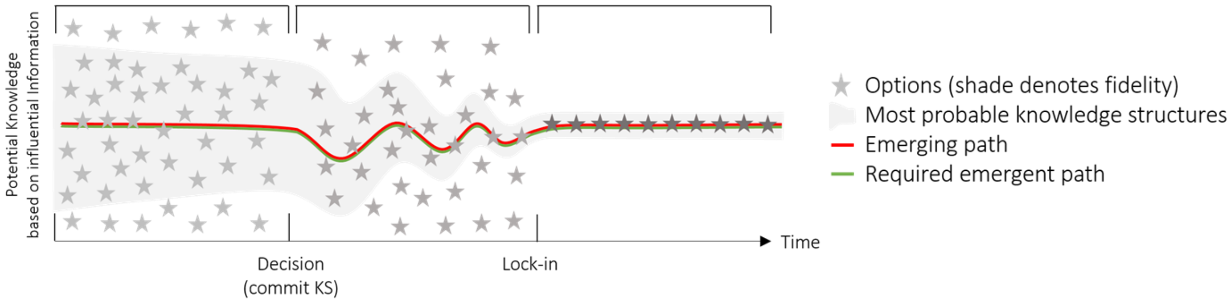

Figure 2. Design path emergence.[1]

Emergent Design Failure is an idea in the field of design theory which describes what happens when significant difficulties emerge during the design process resulting from previously made design decisions.

Emergent Design Failure is characterized by:

1) Excessive Rework - "The repetition (rework) of tasks due to the availability of new information generated by other tasks, such as changes in input, updates of shared assumptions, components, boundaries, or the discovery of errors"[2]

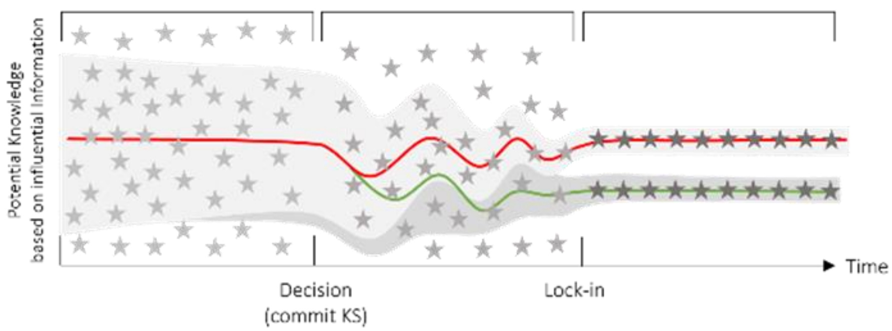

Figure 3. Emergent design path exhibiting excessive rework.[3]

2) Design Churn - "The total number of problems being solved (or progress being made) does not reduce (increase) monotonically as the project evolves over time"[4]

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[1] [3]
[2] [2]
[3] [3]
[4] [1]

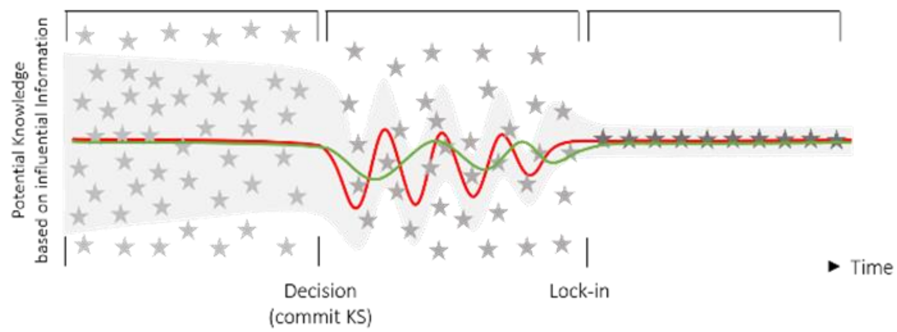

Figure 4. Emergent design path exhibiting design churn.[5]

3) Failure to Integrate – "The inability to integrate a product (component/system) and knowledge required to define that product into the existing design, leading to the inability to continue with current design activities or infeasibility of the final design."[6]

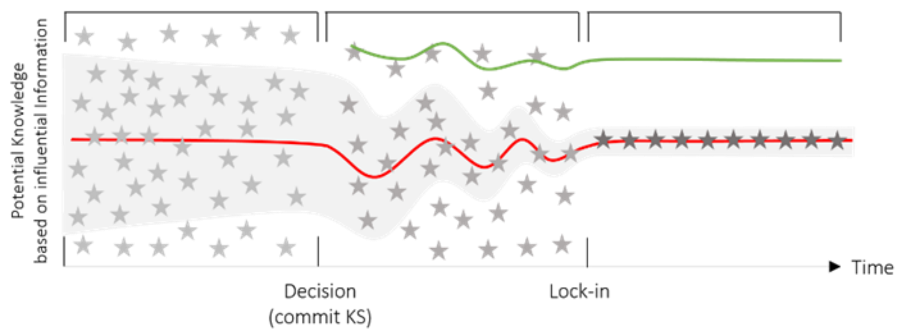

Figure 5. Emergent design path exhibiting failure to integrate.[7]

For this project, an analysis of the path which was followed during the design of the *Sisukas* was conducted. It was concluded that the design of the *Sisukas'* midship cross section exhibited significant design churn, taking much longer than expected to complete.

The Midship Cross Section

In ship design, the midship cross section must satisfy regulatory requirements regarding its ability to resist the vertical bending moments applied to the ship by the ship's own weight, buoyancy and environmental waves. In theory, midship is the location along a ship's length where the greatest resulting moments occur. As shown in the longitudinal load distribution

[5] [3]
[6] [3]
[7] [3]

diagram for the *Sisukas* presented below, the maximum still-water bending moment of the *Sisukas* does occur near the midship point.

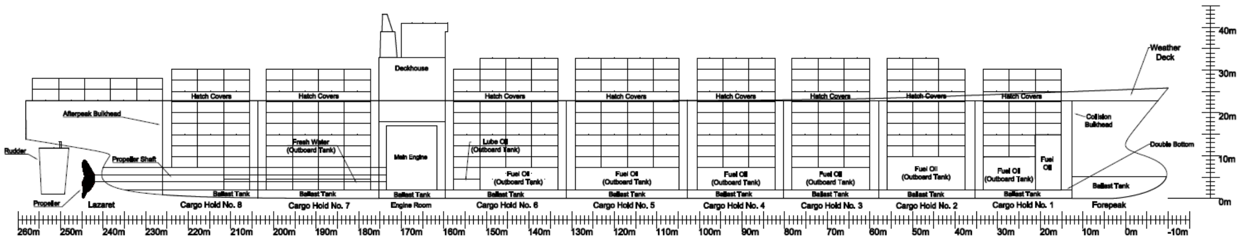

Figure 6. Inboard profile drawing of the *Sisukas*.

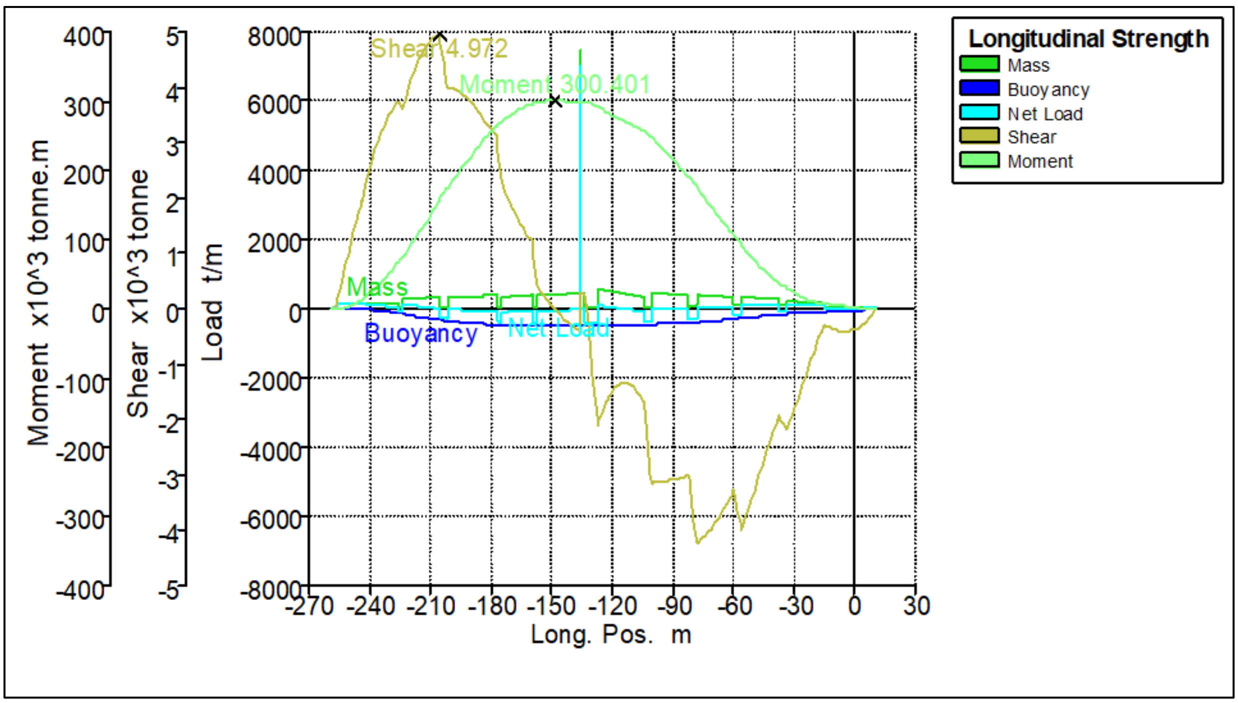

Figure 7. Longitudinal strength and loading diagram for the *Sisukas*.[8]

For this reason, the midship cross section is conventionally used to evaluate a ship's ability to resist bending, and must meet regulatory requirements placed by the American Bureau of Shipping on the cross section's area moment of inertia about its centroid, which represents the ship structure's overall resistance to bending, as well as its section modulus from the area centroid to its deck and bottom plates, which represents the ship structure's ability to avoid buckling of these plates furthest away from the centroid.[9]

[8] [4]
[9] [5]

In the case of the *Sisukas*, the midship cross section proved to take many design iterations to avoid buckling of the deck plating. This was due to the *Sisukas'* abnormally tall depth, which is a measure of the distance from the bottom of the ship to the top deck. Ultimately, a design of the cross section which satisfied the ABS requirements was achieved, but it took much more time and re-designing work than typically expected. The final midship cross section of the *Sisukas* is shown below in Figure 7.

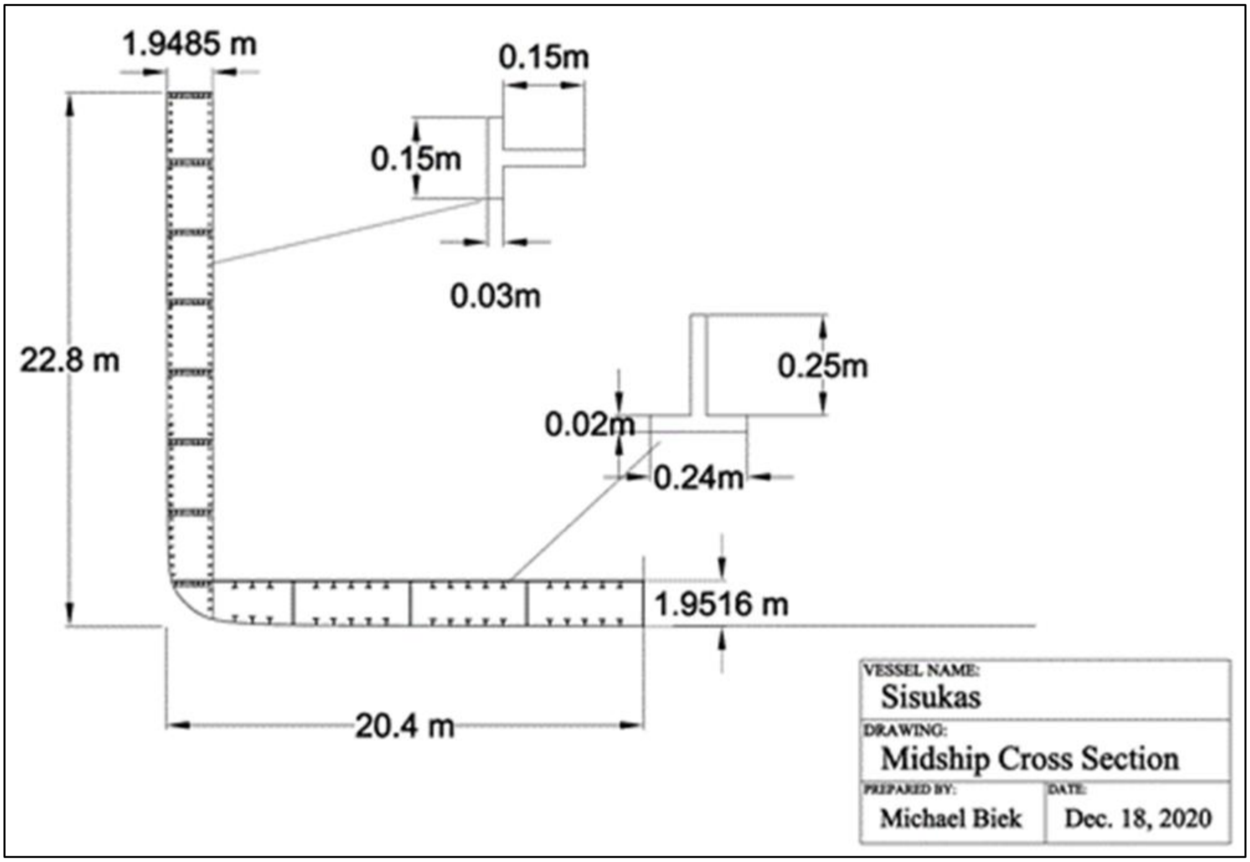

Figure 8. Technical drawing of the *Sisukas'* final midship cross section.

While the ship's large depth made satisfying the overall bending moment of inertia relatively easy, it also resulted in a tendency of the top deck plates to buckle, due to being such a great distance away from the cross section's area centroid. This resulted in the final cross section design having a much greater ware moment of inertia than required to resist the maximum bending moment, in order to supply enough stiffness to avoid the deck plates buckling. The final evaluation calculations for the final design of the cross section are shown on the following page.

Ship Characteristics							
LBP	250	m					
B	40.8	m					
D	23	m					
C_B	0.661						
ABS 3-2-1/3.5.1 - Wave Bending Moment Amidships							
k1	110						
k2	190						
C1	10.396447						
M_ws	-3968953	kN-m					
M_wh	3329508.8	kN-m					
ABS 3-2-1/3.7.1 - Hull Girder Section Modulus							
f_p	17.5	kN/cm^2					
C2	0.01						
14t/TEU Departure	300401	tonne-m	Maximum still-water bending				
14t/TEU Arrival	298539	tonne-m	moments for different loadcases				
12t/TEU Departure	225636	tonne-m	(Calculated by MAXSURF)				
12t/TEU Arrival	228590	tonne-m					
M_sw_max	**300401**	tonne-m	Maximum from load cases				
	2946933.8	kN-m					
M_t	6276442.6	kN-m					
SM(a)	358653.86	cm^2-m					
SM(b)	360813.88	cm^2-m					
SM_min	**360813.88**	**cm^2-m**					
ABS 3-2-1/3.7.2 - Hull Girder Moment of Inertia							
I_required:	**2708812.9**	**cm^2-m^2**					
	270.88129	**m^4**					
Deck and Bottom SM							
Calculated area moment about the Centroid			549.984	m^4			
Deck							
Distance from NA to deck	15.099	m					
Area moment	549.984	m^4					
Deck SM	364251.94	cm^2-m					
Bottom							
Distance from NA to BL	7.766	m					
Area moment	549.984	m^4					
Bottom SM	708194.69	cm^2-m					

Exploration of the Design Path

The next phase of the project was to explore the design path which had led to the *Sisukas'* high depth. The principal dimensions of the ship had been estimated at the very beginning of design. A database of information about existing container ships had been provided to NA 470 students, and regression analyses had been performed using the database to estimate the dimensions for students' ships based on their required capacity of 3,500 14-tonne cargo containers. After estimates for ship length, beam, and draft, were obtained from the regressions, each student used the naval architecture software MAXSURF to parametrically transform a provided cargo ship hullform to match their desired dimensions.

Post-project analysis of this process led to the observation that the initial dimension estimation process for the NA 470 project had been based on the database ships' draft, and not depth. While depth, conventionally denoted as D, is a measurement of the distance from a ship hull's bottom to its top, draft, conventionally denoted as T, is a measurement from a ship's bottom to its waterline. In fact, information about depth had not been included in the container ship database. These two related but different values are illustrated below in Figure 8.

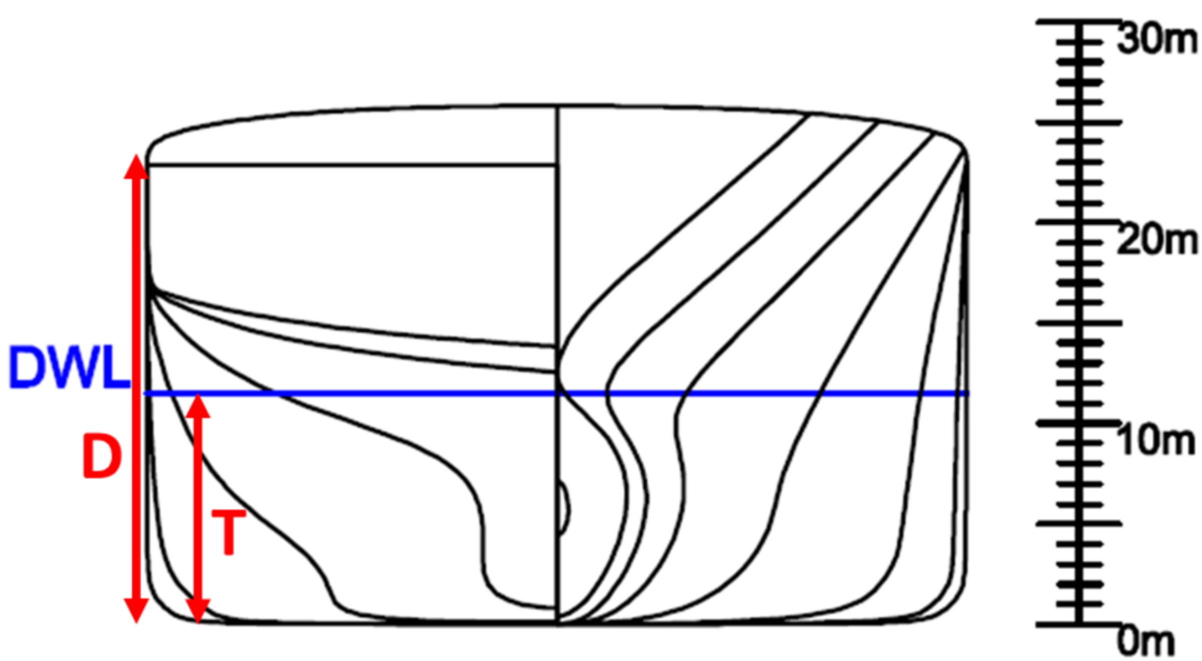

Figure 9. Illustration of depth, D, and draft, T.

For the purposes of this project, the original regression analyses were revisited. Using regulatory requirements, the freeboard of the ships in the original database was estimated. Freeboard is the distance between a ship's waterline and its deck (the difference between draft and depth), and is an important metric for ships' operational safety. It is therefore regulated by maritime safety requirements, primarily the International Convention on Load Lines.[10] For each ship, this value was combined with the ship's draft to produce an estimated depth of the ship. An additional regression analysis of the ships' estimated depth and cargo capacity was performed. On the following page is a comparison of the original draft-based regression with the *Sisukas'* final draft shown, and the new depth-based regression with the *Sisukas'* final depth shown.

[10] [6]

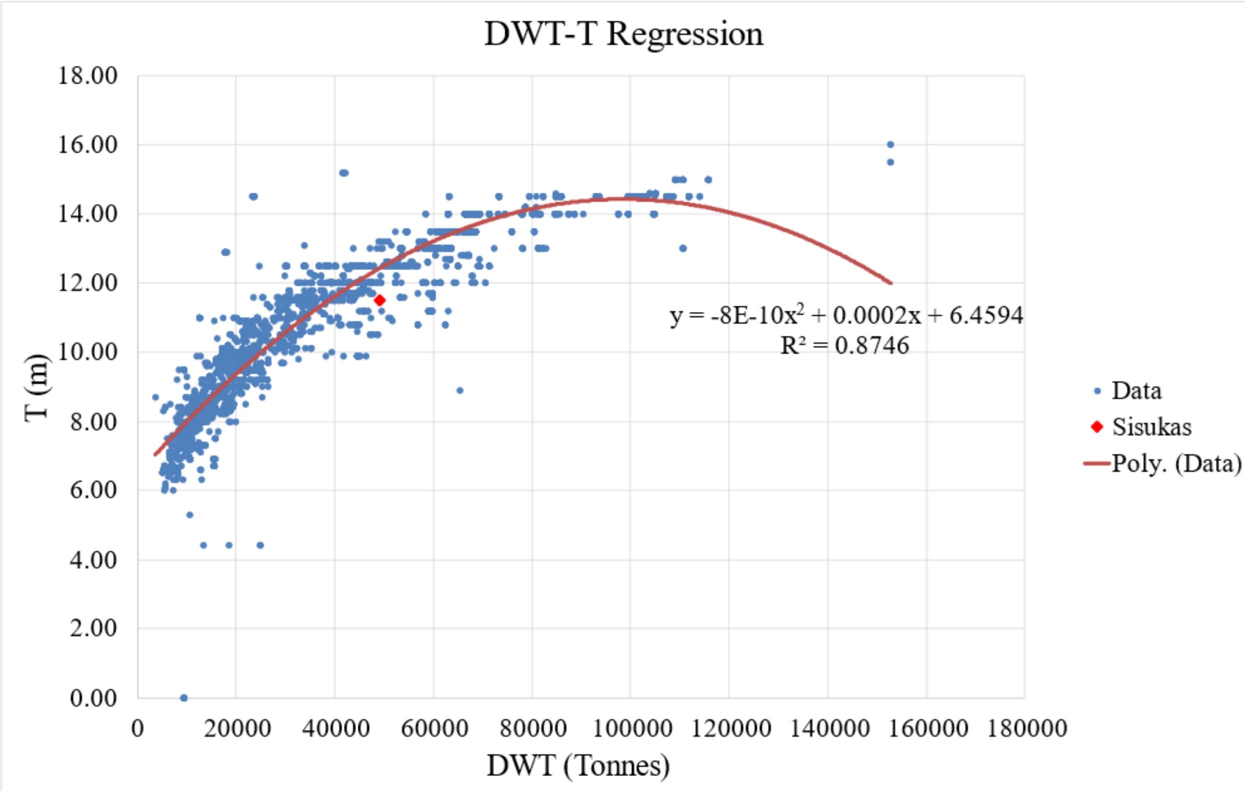

Figure 10. Original regression analysis of draft, T, based on ship cargo capacity, DWT.

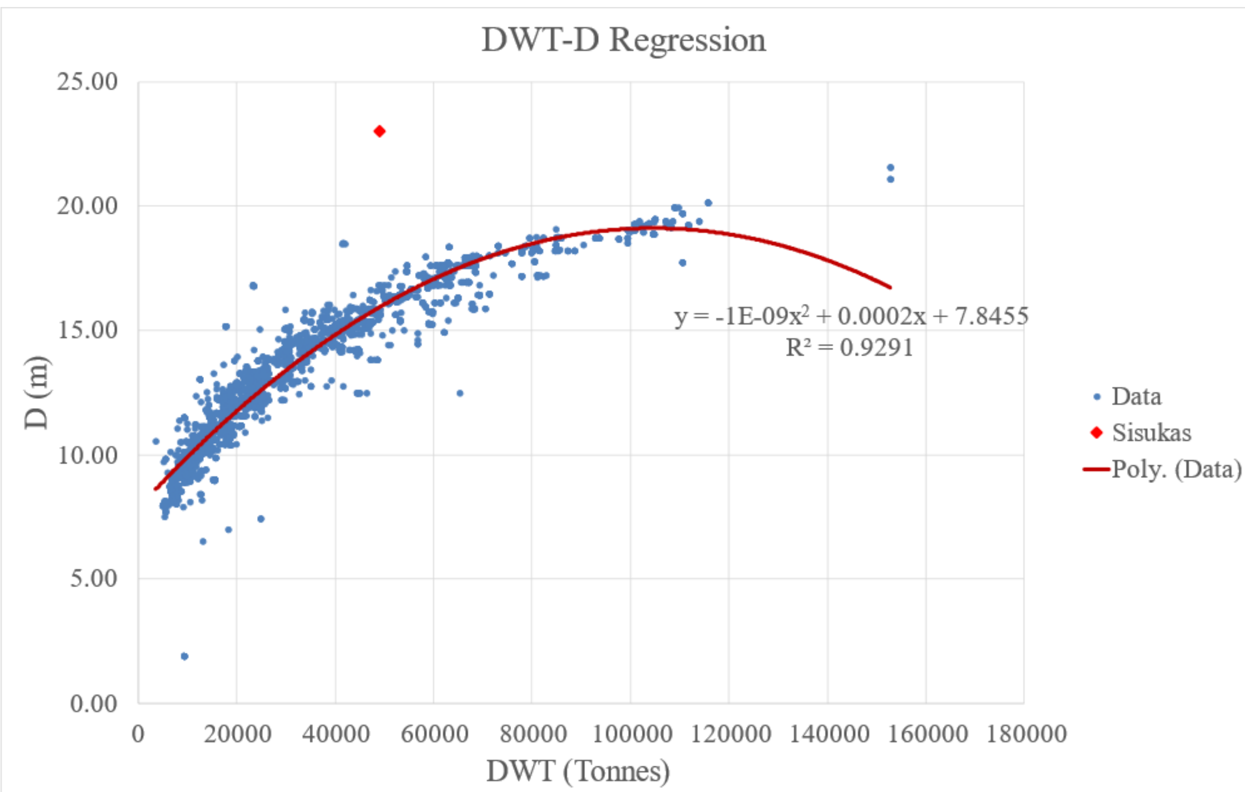

Figure 11. Post-design regression analysis of depth, D, based on ship cargo capacity, DWT.

It can be seen from the graphs that while the *Sisukas'* final draft is within the drafts of other similar-capacity container ships from the database, the *Sisukas'* depth is far beyond the values contained in the data, even beyond the estimated depths of the largest ships in the database. However, the estimated depth data follows a similar trend to that of the draft data. This suggests that the over-inflation the *Sisukas'* depth was not solely due to any invalidity of the original regression analyses, but was also contributed to from another source.

It was subsequently discovered that MAXSURF's parametric transformation functionality holds several other non-dimensional coefficients of performance which describe a ship hullform constant when transforming a hullform. While the parametric transformation process yielded a hullform matching the required length, bean, and draft for the *Sisukas*, it also resulted in an inflated depth. Ideally, the transformation of the provided hullform would have included consideration of the overall depth, and not just the draft, but since depth information was not included in the data available at the time, the design proceeded basing the Sisukas' vertical dimension on draft alone. This disparity was not noticed early in the *Sisukas'* design, and did not cause any issues until the design of the midship cross section near the conclusion of the design project, at which point it was infeasible to change the ship's depth.

Conclusion

In conclusion, the design churn difficulties when designing the *Sisukas'* midship cross section resulted from the emergent design path followed throughout the overall ship design project, and in fact originated in the earliest stage of the design when the principal dimensions of the ship were initially estimated. Regression analysis is a very powerful tool to use in design, but its use is very difficult in situations where many different factors are simultaneously interacting.

In addition, emergent design failures can originate very early in the design process and may or may not be immediately apparent. If they do not cause any immediate issues, such problem can lurk undetected throughout the entirety of the design process until they cause significant issues at much later stages in the design, when it is much more difficult or infeasible to fix them, as occurred in this case.

References

[1] A. Yassine, N. Joglekar, D. Braha, S. Eppinger and W. D., *Information hiding in product development: the design churn effect.,* 2003.

[2] D. Braha and Y. Bar-Yam, *The Statistical Mechanics of Complex Product Development: Empirical and Analytical Results,* 2007.

[3] C. J. Goodrum, *Conceptually Robust Knowledge Generation in Early Stage Complex Design,* Ann Arbor: University of Michigan Department of Naval Architecture & Marine Engineering, 2020.

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[5] ABS, *Rules and Regulations for Building and Classing Steel Vessels,* Spring, TX: American Bureau of Shipping, 2019.

[6] *International Convention on Load Lines 1966,* 1966.