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CASE EXAMPLE IN SYSTEMATIC DESIGN ENGINEERING – LEEBOARD MOUNTING

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1. Introduction

The systematic and methodical design process followed in this case example illustrates the theoretical models usable for design engineering [Eder and Hosnedl 2008, 2010]. This process is only necessary in limited situations [Eder 2009a], but is best learned in a low-threat environment. *Systematic* design engineering is the heuristic-strategic use of a theory about technical products – Engineering Design Science [Eder and Hosnedl 2008, 2010], [Hubka and Eder 1996] is recommended on the basis of an extensive comparison [Eder 2012] – from which a recommended prescription of an engineering design process is derived. *Methodical* design engineering is the heuristic use of newly developed and established methods within the engineering design process, including theory-based and 'industry best practice', strategic and tactical, formalized and intuitive methods. Systematic and methodical procedures overlap, but are not co-incident. The full procedure should be learned, such that the practitioner can select appropriate parts for his/her current applications and design situation.
Creativity [Eder 1996] is usually characterized by a wide search for solutions, especially innovative ones, a search that can be supported by the recommended systematic and methodical approach. All generated alternatives should be kept on record, to allow re-tracing and recovery from subsequent detection or generation of a better alternative. Each step in the overall procedure need not and cannot be completed before starting the next, steps will overlap, iterative working is necessary [Eder 2010a]. New insights from a later step will often suggest improvements for a previous step. Nevertheless, each step should be concluded by selecting the most appropriate (one or two) solutions for further processing, in order to control a tendency towards 'combinatorial complexity'.
The first case example, systematic according to the state of the theory and method at that time, appeared in 1976 [Hubka 1976] – a machine vice. The second was published in 1980 [Hubka and Eder 1992] – a welding positioner. The next three, also systematic, were published in 1981 in German – a riveting fixture, a milling jig, and a powder-coating machine, the first two were systematic, the third took a more industrial-artistic design approach. Another set was published in 1983 – a P-V-T-experiment, a hand winding machine for tapes, and a tea brewing machine – again, the first two were systematic, the third took an industrial-artistic design approach. An English edition was published in 1988 [Hubka et al. 1988], and included the six case examples in these two sets, plus two new items – a wave-powered bilge pump, and an oil drain valve – and again the bilge pump only loosely followed the systematic method. Three further case studies were published in 2008 [Eder and Hosnedl 2008] – the tea machine revised to current procedures showing enhanced engineering information; re-design of a water valve [Eder 2006]; and an electro-static smoke gas dust precipitator, with rapper for dust removal [Eder 2009b]. Three more case examples were published in 2010 [Eder and Hosnedl 2010] – a trapeze demonstration rig [Eder 2010b], re-design of an automotive oil pump [Eder 2010c], and a hospital emergency bed, with compensation devices for the support arrangement. No other methodology known to the author offers any such formalized case examples.

The primary purpose of these case examples is to present examples for procedural application of the recommended engineering design method that students and practitioners can follow and study to help learn the scope of the method and its models. This purpose has been applied in courses at the Eidgenössische Technische Hochschule (ETH) by Dr. Vladimir Hubka (1976-2000, undergraduates), at The Royal Military College of Canada (1981-2006, undergraduates), and at the University of West Bohemia (1990-present, for all levels of university education and for industry consultations). A secondary purpose was to verify and validate the theory and its models, and the method derived from the theory. The emphasis in all case examples was on the engineering design procedure and use of the models, the chosen technical systems in several case studies were not necessarily optimal. Some of the case examples have resulted in manufactured technical systems that have found use in appropriate applications, especially the trapeze demonstration rig, and the example presented in this paper.

The systematic procedure must be adapted to the problem. The cases demonstrate that an engineering designer can idiosyncratically interpret the models to suit the problem, and develop information in consultation with a sponsor. Opinions will vary about whether a requirement should be stated in the class of properties as shown, or would be appropriate in a different class.

This case example is presented to show application of the recommended method, and the expected scope of the output, with emphasis on the stages of conceptualizing. The *embodying/laying out and detailing* stage is regarded as more routine.

The international standard ISO 9000:2005 defines two sorts of technological, artificial, human-made systems, (a) *process systems*, consisting of *operations* – transformation process (TrfP); and (b) *tangible object systems*, consisting of *constructional parts*, with organs and functions – technical systems (TS), if they have substantial engineering content.

The basic model on which the theory and method are based is the general model of a transformation system, TrfS, which declares:

An *operand* (materials, energy, information, and/or living things – M, E, I, L) in state Od1 is transformed into state Od2, using the active and reactive *effects* (in the form of materials, energy and/or information – M, E, I) exerted continuously, intermittently or instantaneously by the *operators* (human systems, technical systems, active and reactive environment, information systems, and management systems, as outputs from their internal processes), by applying a suitable technology Tg (which mediates the exchange of M, E, I between effects and operand), whereby assisting inputs are needed, and secondary inputs and outputs can occur for the operand and for the operators.

Using this model as basis, the stages and steps of a novel design process [Eder and Hosnedl 2008,2010 (figure 11.1, pages 219-221)] are summarized as:

- *task defining*:

(P1) establish a design specification for the required system, a list of requirements;

(P2) establish a plan and time-line for design engineering;

- *conceptualizing*:

(P3a) from the desirable and required output (operand in state Od2), establish a suitable transformation process TrfP(s),

(P3.1.1) if needed, establish the appropriate input (operand in state Od1);

(P3.1.2) decide which operations in the TrfP(s) will be performed by technical systems, TS, alone or in cooperation with other operators; and which TS(s) (or parts) need to be designed;

(P3.1.3) establish a technology (structure, with alternatives) for that transformation operation, and therefore the effects (as outputs) needed from the technical system;

(P3b) establish what the technical system needs to be able to do (its internal and cross-boundary functions, with alternatives);

(P4) establish what organs (function-carriers in principle and their structure, with alternatives) can perform these functions. These organs are found in prior art, especially the machine elements, in a revised arrangement as proposed by Weber [Weber and Vajna 1997, Eder 2004,2005];

- *embodying/laying out and detailing*:

(P5a) establish what constructional parts and their arrangement are needed, in sketch-outline, in rough layout, with alternatives;

(P5b) establish what constructional parts are needed, in dimensional-definitive layout, with alternatives;

(P6) establish what constructional parts are needed, in detail and assembly drawings, with alternatives.

Only those parts of this engineering design process that are thought to be useful are employed. Such an 'idealized' procedure cannot be accomplished in a linear fashion, iterative and recursive working is essential [Eder 2010c]. The suffix '(s)' indicates that this TrfP and/or TS is the subject of interest.

PROCEDURAL NOTE*: Compare the output of each stage with the theoretical figures from [Eder and Hosnedl 2008, 2010] to check whether any important elements may be missing.*

2. Leeboard bearing arrangement

Founded in 1970, the Caravan Stage Company [Caravan] travelled in Canada and the U.S.A., entered a community with horse-drawn gipsy-style caravan carriages, pitched a large (24 *m* diameter) decorated tent in a park, and using the caravans in the tent as their scenery performed self-scripted plays. Around 1992 they decided to have a steel replica of a wooden River Thames (London, England) sailing barge designed and fabricated in a small dockyard in Kingston, Ontario, Canada. It took four years to complete, 30 *m* length, 7.2 *m* beam, 1.3 *m* draft, single mast, fore-and-aft rigged sails, 316 m^2 sail area, about 90 *tonne* displacement. All materials and OEM parts were donated to the Caravan Stage Company, about Cdn$ 2,000,000.00. The newly designed superstructure, mast and rigging were intended to double as the stage for performances, with the audience on shore. The stage barge was to be fully independent, with its own power supply (two diesel motors), lighting and amplification system, galley and sleeping accommodation, etc.

Sailing vessels need an underwater lateral area to react the sideways vector of wind force on the sails. Usually sailing boats have an extended keel under the central lengthwise (bow-to-stern) former to provide the reaction surface. This keel may be fixed, as in most pleasure, racing and passenger sailing craft, or it may be a sliding plate through a central box for small boats.

The original Thames sailing barges carried bulk goods such as coal along coastal waters (from Newcastle-on-Tyne to London). Their reaction surfaces were leeboards, one on each side, suspended that each could be raised around a pivot to lay freely alongside the hull on the windward side, or lowered into the water on the leeward (down-wind) side in its reaction position to rest vertically against the hull. The pivots were pins attached to the leeboard, fitted through a hole in the side of the hull, and the two pins were connected by a chain stretched with sufficient play across the cargo space.

The author was initially contacted in 1994 by Paul Kirby, producer of the Caravan Stage Company, via the Head of Mechanical Engineering, The Royal Military College of Canada (RMC) to help by designing various needed items. Among these (in 1996) was a bearing arrangement to suspend the two leeboards. For the Caravan Stage Barge, the 'cargo space' is used for living accommodation, and the space between the sides of the barge is obstructed by a superstructure to cover the living space. The leeboards must therefore be suspended as unobtrusively as possible.

Steps from the procedural model [Eder and Hosnedl 2008, 2010] were considered, and the following review cycle was applied for each step:

{Improve, optimize} <Substantiate, evaluate, select, decide> {Verify, check, reflect}

(P1) Establish a list of requirements, a design specification – investigate alternatives

Requirements are listed only under the most relevant TrfP and/or TS-requirements class as judged by the engineering designer, and cross-referenced if they are repeated in any other relevant requirement class [Eder and Hosnedl 2010 (Figure 11.4, p. 226-227)]. Indication of priority – F ... fixed requirement, must be fulfilled; S ... strong wish; W ... wish; N ... not considered.

Rq1 OrgRq Organization requirements (Rq1A – Rq1E)
F The project must be accomplished within the available funding.
F Coordination needed between Stage Barge Company and Mech. Eng. Department.

Rq2 TrfRq Requirements of the Transformation (Rq2A – Rq2E)
F Process of assembling the leeboards to be done by Stage Barge personnel.

	F	Process of raising or lowering each leeboard to be done by Stage Barge personnel, also responsible for raising/lowering/securing mechanisms.
	F	Maintenance and adjustment to be done by Stage Barge personnel.
	F	Instructions for assembly and maintenance to be provided by the main engineering designer (W.E. Eder).
	F	Must resist saltwater (coastal ocean).
Rq3	EfRq	Effects requirements of the TS (Rq3A – Rq3C)
	F	Must safely carry weight of leeboard, each with about 700 *kg* mass.
	F	Centerline of leeboard must be able to swing 80E from vertical to just below horizontal (pointing aft).
	F	Leeboard in vertical position must be able to lay on hull (2.5E inward) or swing outward to 3.5E – added in step (P3b).
	F	Leeboard in vertical position must be able to change distance from hull between 25 *mm* (1") and 65 *mm* (2.5"), and be positively returned to 25 *mm* position – movement within 0 and 25 *mm* should be permitted without force – added in step (P3b).
Rq4	MfgRq	Manufacturing requirements
	S	welded and mechanically assembled, machining held to minimum.
	F	Standard machine shop equipment, no special requirements.
Rq5	DiRq	Distribution requirements
Rq6	LiqRq	Liquidation requirements
Rq7	HuFRq	Human factors requirements (Rq7A – Rq7G)
	F	Stage Barge actors/crew to handle.
	F	Safety of crew is essential.
Rq8	TSFRq	Requirements of factors of other TS (in their TrfP) (Rq8A – Rq8G)
	F	Damage to hull and leeboard should be avoided.
Rq9	EnvFRq	Environment factors requirements, LC1 - LC7 (Rq9A – Rq9B)
Rq10	ISFRq	Information system factors requirements, LC1 - LC7 (Rq10A – Rq10F)
Rq11	MgtFRq	Management factors requirements
Rq11A		Management planning, LC1
Rq11B	F	Management of design and manufacturing process, LC2 - LC4, by main engineering designer (W.E. Eder) in cooperation with Technical Officer (O. Koroluk)
Rq11C	S	Design documentation, LC2, kept by both Stage Barge and Mech. Eng. department
Rq11D		Situation, LC2
Rq11E		Quality system.
Rq11F		Information requirements
Rq11G		Economic requirements
Rq11H	F	Must be completely manufactured and tested before mid-April 1996
Rq11J	F	Materials acquired from standard suppliers
Rq11K		Organization
Rq11L		Supply chain requirements
Rq11M		Other management aspects

DesRq Engineering design requirements for TrfP(s) and TS(s) (Rq12 – Rq14)

None.

{Improve, optimize} <Substantiate, evaluate, select, decide> {Verify, check, reflect}

(P2) Establish a plan and time-line for design engineering

Aim for completed design documentation end of February 1996.

(P3a) Establish a suitable transformation process TrfP(s)

All of the operations in figure 1 treat the leeboard as operand (answers to 'what is done to the leeboard?') – in this respect, this case is untypical.

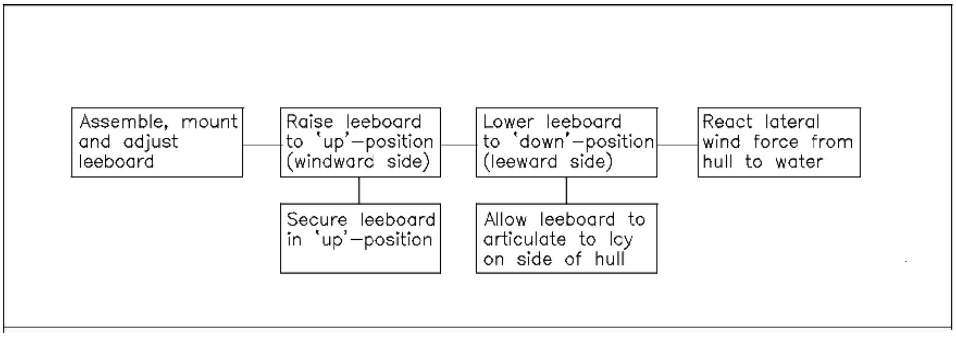

Figure 1. Transformation process (TrfP)

{Improve, optimize} <Substantiate, evaluate, select, decide> {Verify, check, reflect}

(P3.1.3) Establish technology Tg

Pin fixed to leeboard, loose fit in hole in hull (replace cross-cargo-space chain)
Concept (a) – cable connection between leeboards
Concept (b) – cable to counter-weight in guide tube
Pin fixed to leeboard, bearing arrangement at hull
Concept (c) – gimbal mount plus spring
Concept (d) – self-aligning bearing plus spring

(P3b) Establish TS-internal and cross-boundary functions – with alternatives

In figure 2, the leeboard is now the technical system as operator (answers to 'what can the leeboard and its mount do?').

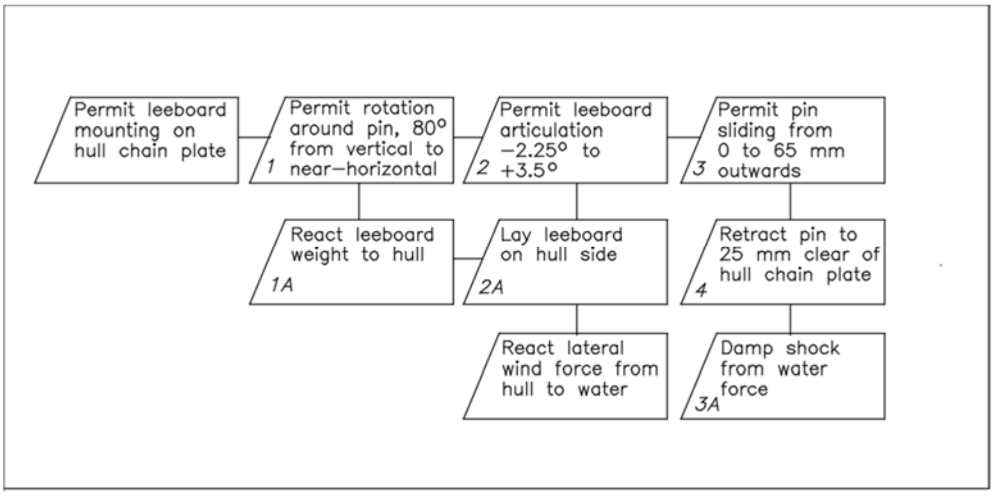

Figure 2. TS-Function structure (FuStr)

{Improve, optimize} <Substantiate, evaluate, select, decide> {Verify, check, reflect}

(P4) Establish Organ Structure – with alternatives

Figure 3 shows alternative ways of operating each of the solvable TS-functions, as numbered in figure 2 (answers to 'with what means-in-principle can the functions be realized?'). No formalized selection method was used.

The self-aligning roller bearing is less suitable, it does not take substantial axial forces and is sensitive to brinelling (local indentation of the raceways) from non-rotating shock loads.

The original arrangement of a simple (reinforced) hole in the chain plate is unsuitable, it provides too much freedom of movement, and may lead to uncontrolled wear.

TS-Function	Action Principles and Organs			
1 Permit rotation 80 from vertical 1A React leeboard weight to hull	Sliding journal bearing	Self-aligning (spherical) roller bearing (2-row)		Reinforced hole in hull chain plate hull leeboard and pin
2 Permit articulation +2.5 to − 3.5 2A Lay leeboard on hull side	Sliding spherical bearing			
3 Permit pin sliding 3A Damp shock from water	Axial sliding journal bearing	(empty)		
4 Retract pin to 25 mm position	Cable con-necting two leeboards	Cable and weight for each leeboard	Helical spring	Belleville disk springs in series

Figure 3. Morphological matrix

Suitably combining the means from figure 3 allows exploring the TS in a skeleton form, see figure 4

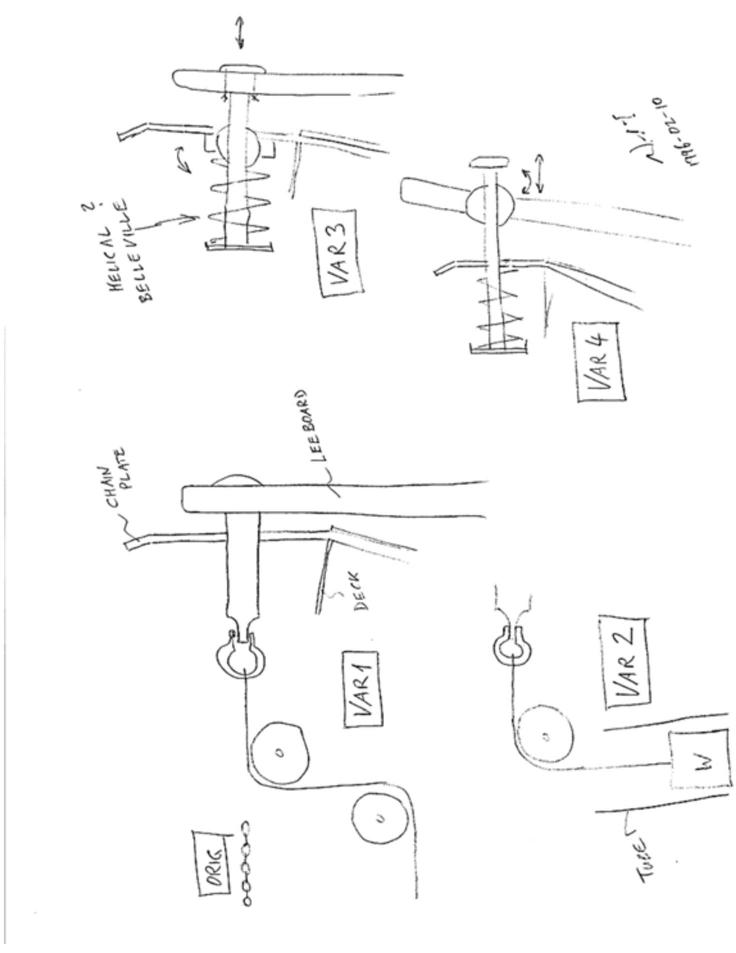

Figure 4. TS-Organ structures (OrgStr)

Again, no formalized selection method was used.

Variation 1 in figure 4 is closest to the original Thames cargo sailing barge, but requires a cable or chain duct under the living space across the beam of the barge – undesirable.

Variation 2 uses a weight guided in a tube to provide the retraction force – the noise of a weight hitting the inside of the tube (even at anchor) would be very disturbing for the crew – undesirable.
Variation 3 uses a spherical sliding oil-lubricated (and porous oil-retaining) bearing mounted on the hull, and uses the internal diameter to provide longitudinal sliding of the pin, with (a) helical or (b) Belleville disk springs to give the retraction force – preferable, and selected for layout.
Variation 4 uses a spherical sliding oil-lubricated (and porous oil-retaining) bearing mounted in the leeboard – difficulty keeping sea-water out of the bearing – less desirable.

{Improve, optimize} <Substantiate, evaluate, select, decide> {Verify, check, reflect}

(P5a) Establish Constructional Structure in rough layout – with alternatives

Drawings of the proposed leeboard, see figure 5, and of the hull arrangement at the leeboard location, see figure 6, were provided by the Caravan Stage Company.

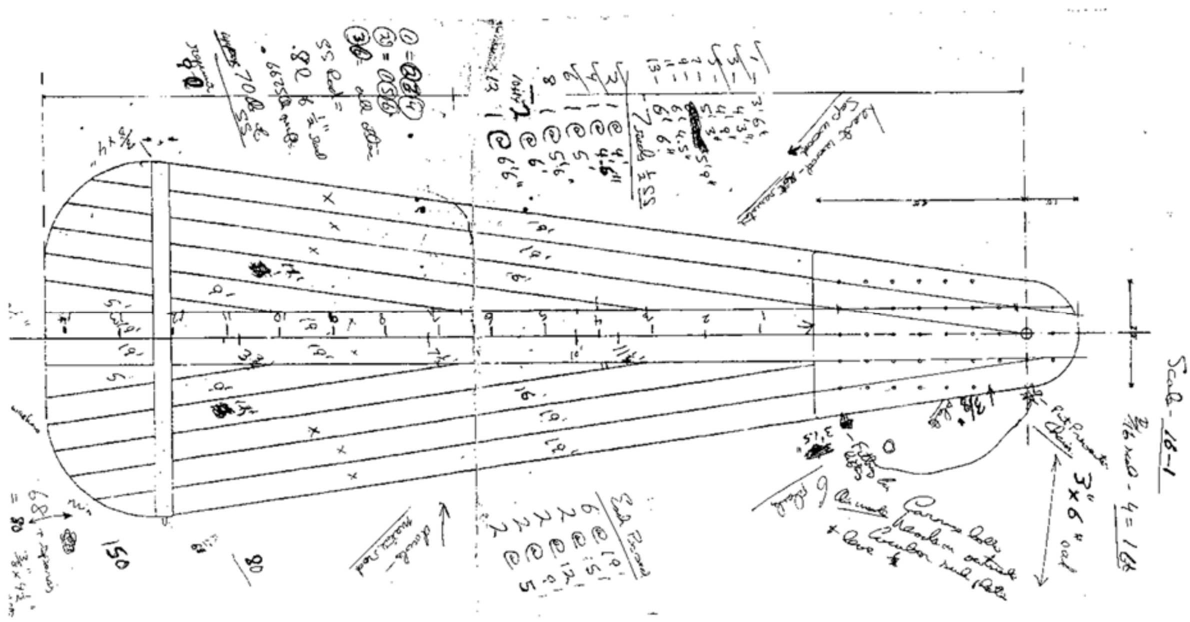

Figure 5. Leeboard

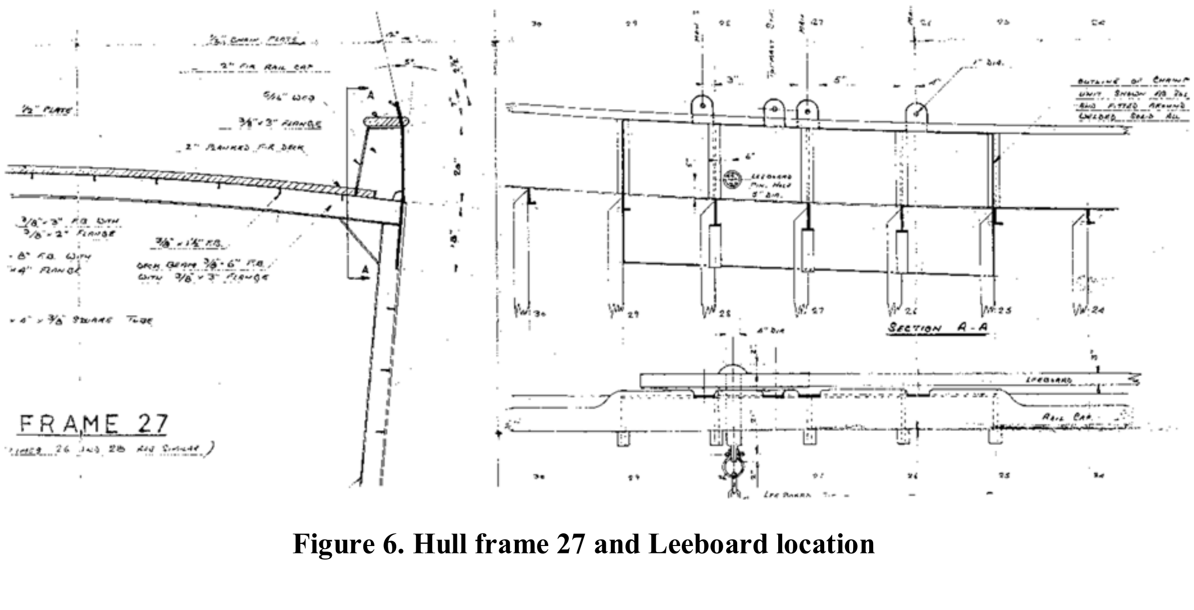

Figure 6. Hull frame 27 and Leeboard location

(P5b) Establish constructional structure in dimensional-definitive layout – with alternatives

Based on the best of several sketch layouts, the dimensional layout of figure 7 was produced.

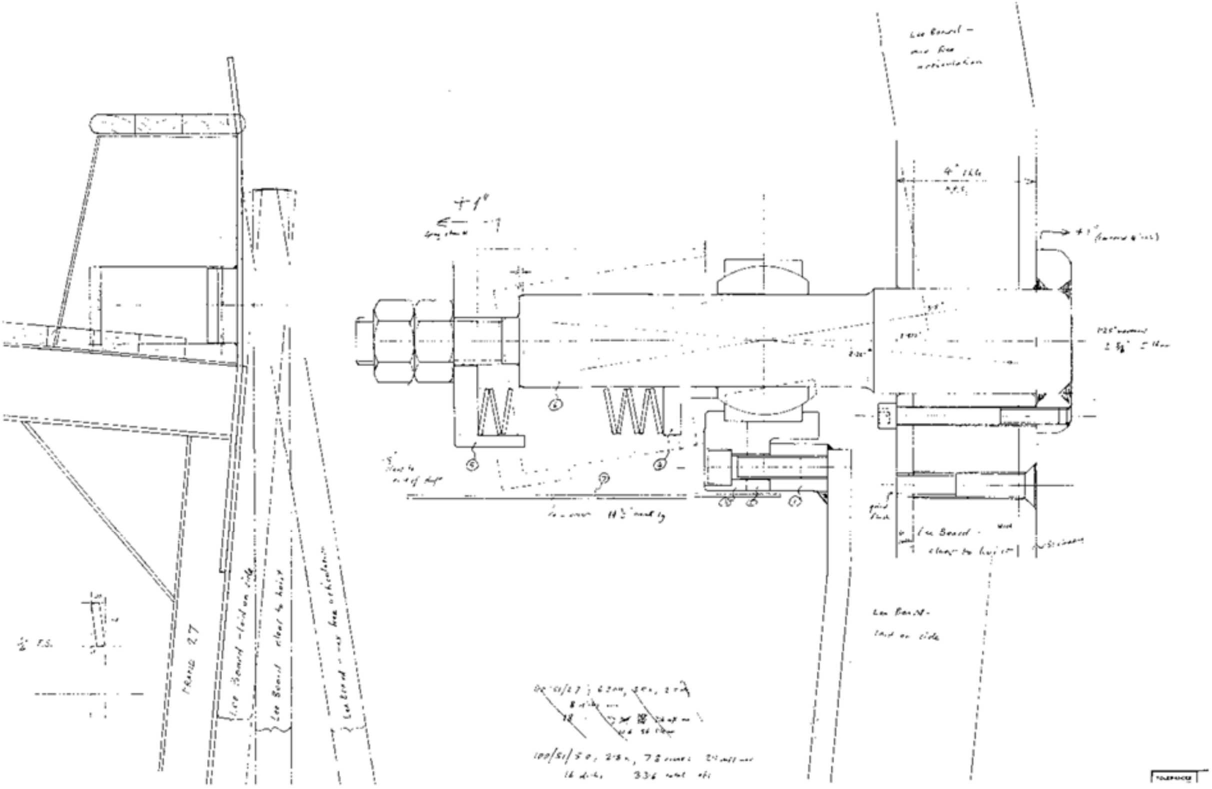

Figure 7. Layout of leeboard mounting

{Improve, optimize} <Substantiate, evaluate, select, decide> {Verify, check, reflect}

(P6) Establish constructional structure in detail and assembly drawings – with alternatives

Even though computer graphics were available, detail drawings were prepared by hand with pencil on paper – a repeat use for this project was not anticipated. figure 8 shows the final assembly drawing with parts list. figure 9 shows the modifications needed for the chain plate on the hull.

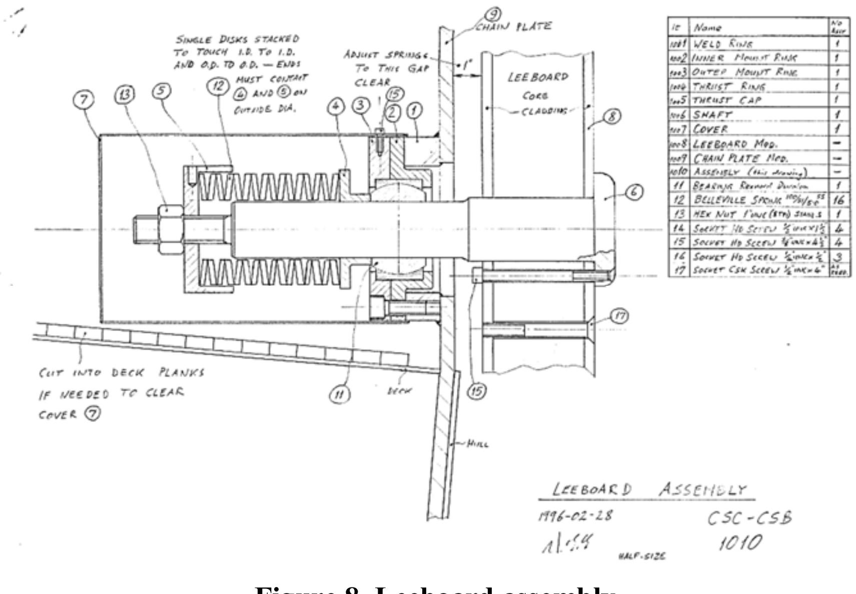

Figure 8. Leeboard assembly

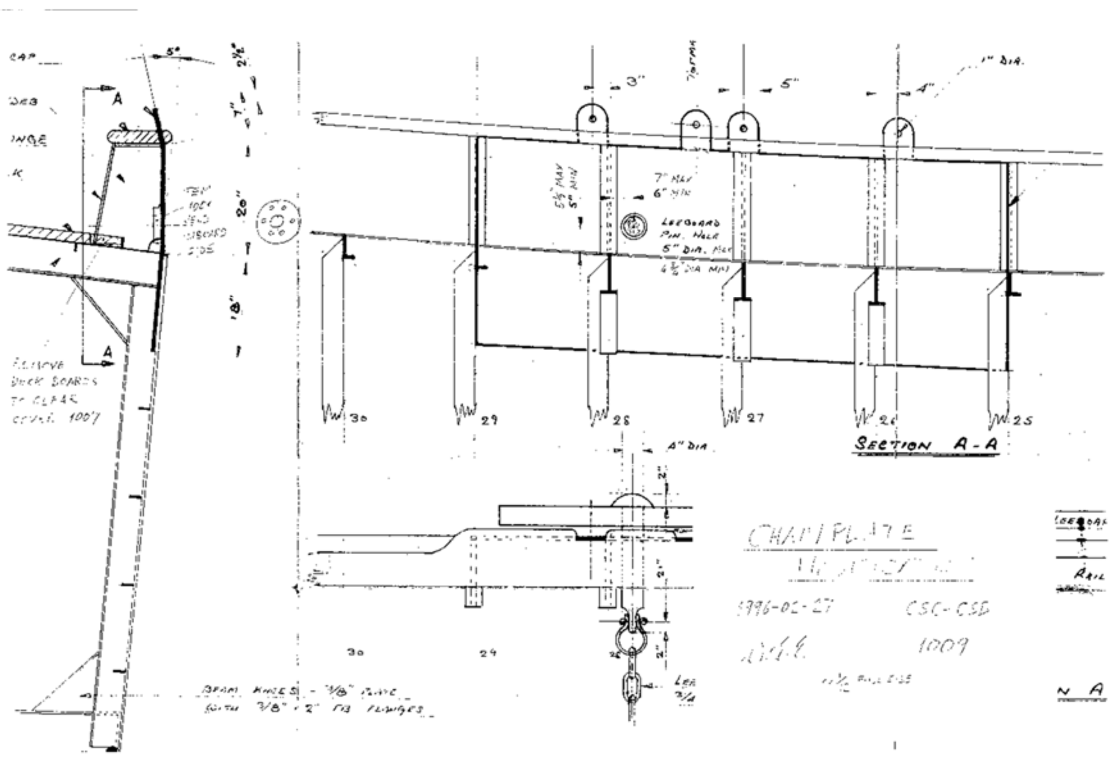

Figure 9. Chain plate modification

{Improve, optimize} <Substantiate, evaluate, select, decide> {Verify, check, reflect}

3. Closure

The launch of this stage barge was successful. The Company has since then toured the Great Lakes, and the Atlantic and Pacific coasts of the U.S.A. and Canada. It is currently touring in Europe and the Mediterranian regions [Caravan].

This case example demonstrates that a systematic and methodical engineering design process can be usefully applied, especially if the designer's situation demands risk or safety operation [Eder 2009a]. Systematic design engineering allows a wide search for alternative solutions, and is potentially a good tool for engineering education.

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