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Synergy-Based Design of Light Fittings

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Abstract
The aim of the present paper is to give an overview of the testing results of the developed methodology of interdisciplinary products and systems design striving for the synergy of allied technologies. The proposed design methodology has its sources in the integration of the Design Structure Matrix technology and the Theory of Design Domains refined by the synergy based way of thinking. It allows developing a new family of adaptive design tools based on the level of competence and expert knowledge of the design team and synthesize their own roadmap algorithm to move ahead on the way of the synergy-based design process. In the paper the results of the testing of the proposed methodology for the design of light fittings are presented. The guidelines of completing the design structure matrixes in synergy context are specified in detail and advice is given about empowering the synergy approach. The involvement of human factors and market relations in the whole design process and their influence on the prognosis of its timing are analysed. The conclusion has been reached that the proposed methodology is ready for wider industrial use.

Keywords: product development, interdisciplinary systems, synergy-based design, design structure matrix analysis

1 Introduction
The increase of the integration of different technologies in new products with better performance and marketing power due to the exploitation of the best features of allied technologies has been an ever-growing tendency during the last decades. Around the beginning of the present century the engineering design research community reached the somewhat confusing conviction that engineering design is not a pure technical problem any more but a complex activity, involving artefacts, people, tools, processes, organisations and conditions of the real economic environment [1;2]. In the launched race between research groups to fill this gap the present research team has contributed with a new paradigm – the synergy-based approach to design [3]. This design methodology is founded on an original idea - taking the evaluation of the quantitative characteristics of positive and negative synergy of allied technologies as a basis to develop the design methodology making it possible to regulate the synergy balance and to develop products of enhanced functional quality and competitive power. The synergy-based approach makes it possible to bring design parameters, market conditions, human factors, reliability problems, etc under one umbrella.
The main three key features of the synergy-based design methodology are as follows: effective and continuous handling of synergy and market information of allied technologies, involvement of synergy-based treatment of human factors during the whole course of task-

sequencing of the design process and prognosis of the development duration taking human aspects into account. The conclusion was reached that it is suitable to base the planned design methodology of complicated interdisciplinary products on the Design Structure Matrix (DSM) technology which enables to describe the synergy-based interrelations between allied technologies exactly enough [3;4]. Due to the outstanding capabilities to clear up the sequencing and modularisation processes the use of the matrix methods has become more and more popular [5;6;7].

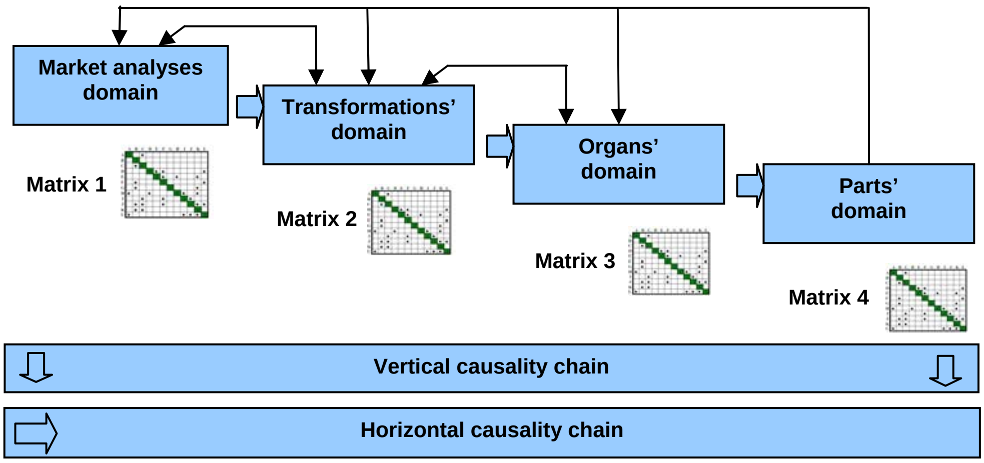

Figure1. The integrated model of interdisciplinary systems design

For the framework of the design activities it was necessary to find a high level design tool where it is possible to involve the systems' engineering approach to make it possible to control the advance in the 3-dimensional design space: not detailed-detailed, abstract-concrete and by steps of the realisation of the artefact. A suitable basis for it appears to be the Theory of Design Domains (TDD) proposed by Andreasen [2;8]. This theory is based on applying three views of the product – transformations', organs' and parts' domains encompassing substantial classes of structural definitions and behaviours of the artefact. The TDD makes it possible to link the engineering designer's considerations about the interdisciplinary system (delivering effects for the purposeful transformation) via considerations about organs (creating effects) to considerations about the parts being produced and assembled. By integrating the DSM technology and the TDD it is possible to create a good design environment for interdisciplinary systems design (see in Fig. 1). This model makes it possible to take into account both "soft" parameters of design - market conditions and human aspects. In the added domain of market analysis matrix 1 presents the activity-type DSM that allows to take marketing trends into account and to initiate the synergy-based activities in the firm's product strategy planning so that the developed products should be competitive on the market. Matrix 2 in transformations' domain is a parameter-based DSM that gives an algorithm for the design process and makes it possible to reach the optimal synergy level and performance of the product designed. Matrix 3 in organs' domain represents parametrical activities in the selection of the suitable active elements or organs and their mode of action for interdisciplinary artefacts. Matrix 4 in the part design domain is focussed on the allocation or distribution of the organs in the parts, which can be produced and assembled so that all the system's performance tasks are solved and its totality behaviour assured. In Fig.1 the vertical causality chain proposes the use of Vertical Causality Law [8] through Functions Means Tree as its graphical representative. The horizontal causality chain represents the involvement of the systems' engineering approach in the control of the advance of design. By integrating the

DSM technology and TDD it has been possible to create a novel generic environment for the design of the interdisciplinary systems on the border of the prescriptive and descriptive design environments. In the above-mentioned environment it is possible to develop a category of adaptive design methodologies based on the synergy-based synthesis of the decision-making algorithm depending on the competence of the design team. In this environment it is also possible to prognosticate the duration of the competitive product development, which depends on the optimal (market-driven) level of synergy and quality, taking human factors into account too. In this process the statistical probability evaluation of the time for iterations, reworks and learning may be used [9] taking into account the negative synergy effects - human faults and mistakes.

The most important recommendation for any use of design methodology is its testing in the industrial environment. In the present paper the results of the complete testing of the entire synergy-based design methodology on the basis of the light fittings design was provided. Despite seeming simplicity modern light fittings are a clever integration of mechanical support structure with optics, thermal engineering and electronics.

2 On completing the DSM in synergy context

For the market analysis domain the DSM for 16 inputs was compiled, characterizing trends in the present market environment, the product strategy of the company and its personnel's competence in product development. The expected outcome from the synergy-based approach of this analysis is to work out the company's external and internal product policy and activities to manage risks in conditions of the decreasing or increasing market.

Task Name		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Market expects smaller size of light fittings	1		1					2	1		1	1	2	1	1	1	
Market expects better quality of lightening	2	1						2			1	1	2	1	1		
Market needs cheaper light fittings	3	1			1			2			2	1	1	1		1	
Market needs multifunctional light fittings	4			1				2		2	2	1		1		1	1
Market expects light fittings with easy mounting	5							2	1		1			1		1	
Simplified service of light fittings	6				1			2	1		1			1		1	
To increase the light fittings customization	7					1	1		2		2	2	1	1	1	1	
Positioning of the product on a higher level in the market	8									1	2	2	2	1	2	1	1
Bought-in technology transfer	9															1	1
Companies' market share expansion strategy	10								2			2	2	1			
Empowering of companies' product development capability	11								2		2		2		1	2	2
Competence level of companies' needs to be increased	12														2	1	1
Product needs modernization	13														1	1	1
Product development needs advanced scientific research	14												2	1			1
Development of synergy based communication ability	15																2
Development of the inside synergy of the team members	16															2	

Figure 2. The market relations' DSM before sequencing

There is no need to arrange inputs in order as it is sequenced by mathematical treatment of the matrix. All inputs must only be preliminarily numbered to give a possibility to involve the synergy relations between inputs in the matrix and therefore the numbers of inputs must be the same on vertical and horizontal axes. The number of inputs is practically not limited and depends only on the complexity of the product. However, first of all it is necessary to define the concept of "synergy" used in the present context. Linguistically the word "synergy" marks the situation when the summary effect of different factors due to their mutual empowering is greater than their sum. Sometimes it is called 2+2=5 effect. Generic foundation of positive synergy is optimisation in its wider interpretation including its logical, mathematical and physical basis. The traditional way is logical optimisation that has always been used in any design process. In complicated situations, outside the brain's seizure, we have to apply mathematical tools. The precondition for granting physical synergy at the different technologies interaction is knowing the gist of integrated processes on such a level that it is fully possible to control these processes. In reality all these three approaches complement each other, calling forth a total synergy of performance.

Anyway, it is not possible to ignore negative synergy facts due to their insidious action. Negative synergy is closely related to the reliability characteristics of the system and it reveals itself mostly in the infant mortality period of a new product's life cycle [10] and during the aging of the product. In the synergy context reliability can be treated as a process where the synergy of operation of components is gradually reducing (wear, emission, etc) and stops functioning when accumulating negative synergy reaches its extreme value.

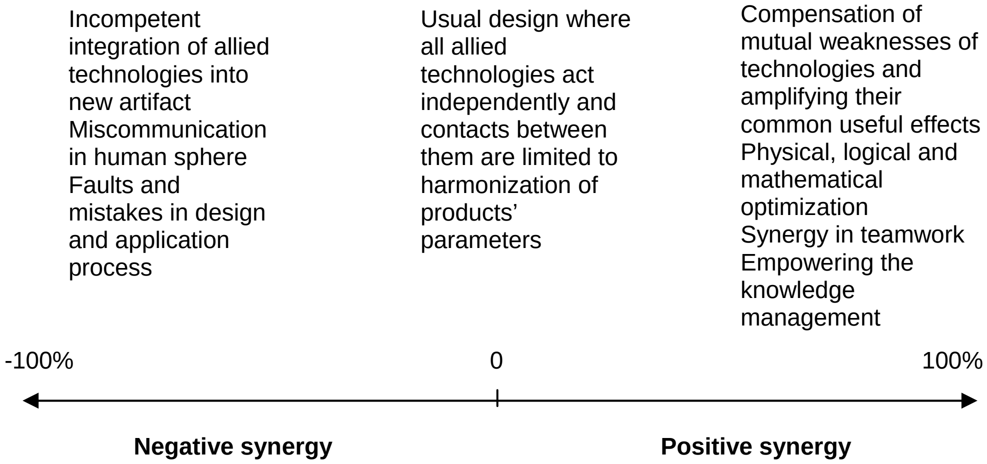

Figure 3. Positive and negative synergy deployment

The essence of the synergistic approach to interdisciplinary systems design is seen in Fig. 3. One of the requirements for moving ahead in synergy-based engineering design methodologies is to use quantitative characteristics of synergy. Quantifying the synergy in artefacts proposes the existence of a synergy evaluation tool and universal scale to measure the products' performance. The scale of measuring may start from 0 for a conditional interdisciplinary synergy-free product. For the evaluation of positive synergy it is the most purposeful to use a relative parametrical scale based on the benchmarking of similar products on the market. The maximum value on the positive side of this scale means reaching the maximum synergy (100%) where everything has been squeezed out of physical processes. Our practice has shown that a 3-step scale for synergy relations is quite optimal. All interactions between inputs in matrixes must be evaluated from the synergy point of view. So far it is suitable to distinguish three categories of synergy integration: 0 – synergy is small or absent at all (not filled in matrixes), 1 – synergy is moderate and 2 – synergy is very strong and decisive for the product's or system's performance.

In the whole design process it means that it is necessary to apply the main brainwork effort to attain the synergy allocation having in sight the framework written in the right column of Fig. 3. However, while writing the synergy interfaces it is necessary to take some limitations into account and to be very critical at separating substantial interrelations from inessential ones and take care of inputs reasoning. If we excessively fill in all the squared area, then we may reach the only matrix that is impossible to sequence. The reasonable fill-in succinctness seems to be around 1/3 of the field. It is extremely reasonable to distinguish coupled activities from those which may be solved serial or parallel way. Any incorrectly fixed interface aggravates the attaining of the optimal synergy in the designed product.

3 Sequencing of the design activities for technologies integration

In Fig. 4 the activity-based matrix for market analysis (see Fig. 1), already allocated to sequencing transformation, is shown. In this transformation process activities are ranged with the goal to move all interactions under the diagonal that leads to the possibility to use the information of previously completed actions in a chain of activities. Sometimes parallel actions are possible. In some cases the solution of the current task needs some feedback information from the later activity and those bounded tasks are grouped into outlined blocks. However, it is necessary to remember the main goal of the present research - to reach the optimal synergy between all interactions on all levels of problem-solving.

Task Name	Level		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	
Development of synergy based communication ability	1	1		2			Block1												1
Development of the inside synergy of the team members	1	2	2																2
Competence level of companies' needs to be increased	2	3	1	1			2			Block2									3
Product needs modernization	2	4	1	1			1												4
Product development needs advanced scientific research	2	5		1	2	1													5
Bought-in technology transfer	2	6	1	1									Block3						6
Positioning of the product on a higher level in the market	3	7	1	1	2	1	2	1		2	2								7
Companies' market share expansion strategy	3	8			2	1			2		2					Block4			8
Empowering of companies' product development capability	3	9	2	2	2		1		2	2									9
Market expects smaller size of light fittings	4	10	1		2	1	1		1	1	1		1					2	10
Market expects better quality of lighting	4	11			2	1	1			1	1	1						2	11
Market needs cheaper light fittings	4	12	1		1	1				2	1	1			1			2	12
Market needs multifunctional light fittings	4	13	1	1		1		2		2	1			1				2	13
Market expects light fittings with easy mounting	4	14	1			1			1	1								2	14
Simplified service of light fittings	4	15	1			1			1	1					1			2	15
To increase the light fittings customization	4	16	1		1	1	1		2	2	2					1	1		16
			1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	

Figure 4. The activity-based market analysis DSM after sequencing

Now we have reached the first goal –all activities are sequenced and grouped on the levels, marking the decision-making steps. In the present case it is necessary to provide the analysis of the design team's competence on the first level and all problems with product development capability and personnel upgrading problems should be solved. The two next levels form an invisible block of the SWOT analysis where on the second level the focus is on the company's inside and on the third level on the outside activities on the market. On the last level decisions have to be made about the concepts of product modernization.

In Fig. 5 the parameter-based transformations' DSM after sequencing is presented. The expected outcome from this analysis is a proposal for the structure of a more excellent device at a moderate price raise. On the first level the block of the initial light quality parameters is formed. The second block is a real design matrix where all important design parameters supporting the performance of the product are presented. The focus of this level's activities is the key problem for light fittings – to solve thermodynamic problems by making a compromise between its dimensions and limited temperature level for its components. The last level carries the feature of output parameters where variations of the principles of montage and additional functions or protection are estimated.

Task Name	Level		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	
More uniform lighting	1	1		2				Block1														1
Light focussing to sides	1	2	2		1																	2
Light fittings with open design	1	3	1	1																		3
Moisture and dustproof fitting	2	4			1		1	1	1	1			Block2									4
Reduction of the light fittings sizes	2	5	1	1	1	1		2	2	1												5
For the heat balancing the increase of the light fitting surface is needed	2	6			1	1	2		1													6
Heat transfer through the construction	2	7				1	2	1		2												7
Installation of light fittings to the combustible base	2	8				1	1		2													8
Unified mounting	3	9										1	1	1	1					Block3		9
Installation of light fittings to the non-combustible base	3	10					1		1		1											10
Installation of light fittings to the montage bus	3	11				1		1	1		1											11
Installation of light fittings into the ceiling cavity	3	12				1		1	1		1											12
Installation of light fittings by hanging	3	13				1		1			1					1	2					13
Standing for the stability of the of light fittings installation	3	14													1							14
Protection of light fittings against vibration	3	15													2							15
Safety lighting function	3	16					2	1	1													16
Programmable light intensity illumination	3	17				1	1															17
Control of light fittings by motion detector	3	18				2	1															18
Protection of light fittings against current instability	3	19				1	1															19
			1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	

Figure 5. The parameter based transformations' DSM after sequencing

In Fig. 6 the organs' domain DSM is presented. The focus of this matrix is to choose the most suitable physical effects for the realization of these functions selected at the analysis of the previous matrix. On the first level all assembly problems are gathered including the way of montage with allocation to the producing, assembly and service quality of the parts. On the second level the main attention is paid to choosing the physical principle of the light source integrated with the housing, reflection quality and electrical communications. The third level is fully focused on light quality forming systems using different reflection systems. As one can see the solution of the described problems paves the way to the detailed design and assembly drawings.

Task Name	Level		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	
Apparatus holder is integrated with housing	1	1		1	1	1		1				Block1											1
Separate apparatus holder	1	2	1		1		1	1	1														2
Mode of apparatus installation	1	3	1	1			1	2	1														3
Installation of the socket / sockets	1	4	1					1															4
Manufacturing-ability of light fittings details	1	5						2	1														5
Assembly-friendly light fitting	1	6					2		1														6
User-friendly light fitting	1	7			1			1															7
Conversion of electricity by luminophore tube	2	8		1	1	1		1			1	1	1		1				Block2				8
Conversion of electricity by high intensity discharge lamp	2	9	1		1	1		1		1		1	2	1	1								9
Casted housing	2	10			1	1	1	1	1				1			2							10
Assembled housing	2	11			1	1		1	1	1		1				2							11
Joining reflective surface with housing	2	12										1	1										12
Type of electrical installations	2	13						2	1		1									Block3			13
Ensuring the dust and humidity protection	2	14					1	1	1				2										14
Reflector with mirroring surface	3	15					1	1			1										2	1	15
Light reflective by dispersion by aluminium surface	3	16																	1			1	16
Smooth reflective surface	3	17																1		1	1		17
Integral reflective surface	3	18																				1	18
Corrugated reflective surface	3	19					1				2						2		1	1			19
Assembled reflective surface	3	20					1	1	1										1	1			20
			1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	

Figure 6. The organs' domain DSM after sequencing

In Fig.7 the last DSM – the details' domain one is presented. It is reasonable to allocate this matrix to the structuring as it serves also the interests of product modularisation. For the present case only three tasks may be differentiated – mechanical and electrical design but with some interfaces between these blocks for carrying the idea of technologies integration.

Task Name	Level		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	
Holding	1	1		2	2	1	1	1	1			Block1												1
Holder for components (on socket side)	1	2	2					1																2
Holder for choker	1	3	2																					3
Clamp for once-through wiring	1	4	1																					4
Tightening silicone	1	5	1																					5
Fastening with screws	1	6							1															6
Fastening with welding	1	7	1			1		1																7
Reflector	1	8									2	1	1			Block2								8
Reflector fixing frame	1	9								2														9
Glass cover	1	10								1			2							Block3				10
Glass fastening (hinges and screws)	1	11								1		2												11
Choker	2	12			1													1						12
Socket	2	13		1														1		2				13
Starter	2	14		1														1						14
Condenser	2	15		1														1						15
Wiring	2	16												1	1	1	1		1					16
Terminal board	2	17	1															1			1			17
Lamp	2	18													2									18
Feedthrough	2	19	1																1					19
Glass seal	2	20	1																					20
Temperature proof wiring with protective cover	3	21				1											1		1					21
			1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	

Figure 7. The details' domain DSM after structuring

It is also necessary to pay attention to the fact that process sequencing is only the first step of the design process. In any case a trustworthy roadmap for the design process has been created giving a possibility to keep a comprehensive overview of the decision-making process. As a matter of fact, for this case we have been able to distinguish 12 groups of decision-making levels and 75 design tasks with 279 interactions where we have to look for synergy-based interaction.

However, while using the proposed tool it is necessary to be aware that the composing of the useful and suitable DSM is a complicated process, sometimes time-consuming and this may be a great challenge for a design team. So the professionalism is simultaneously needed in product architecture, product development process and organisational work and the success in using the design model depends on the existence of these qualifications. The low competence of the design team may result in an imperfect DSM where some important interactions may be absent or incorrectly evaluated. It is natural that the design outcome depends on the design team's capability.

4 Timing of the development process

An important part of the described synergy-based design methodology is the prognosis of the development time. Depending on the preparedness of the design team to handle the matrix analysis and mathematical statistics there are 3 possible levels of the use of the proposed methodology. On the first level and for a comparatively simple product it is possible to fill in only the DSM with synergy interactions and to sequence design tasks by hand using for the prognosis of the development time the experience of completing previous similar design tasks. Also, on this level it is possible to exploit the fruits of synergy-based thinking. On the second level the mathematical matrix analysis is necessary for task sequencing. For complex products and systems out of the brains seizure it seems to be the only real possibility. The use of the opportunities of the third level needs additional experience in probability evaluation and discreet event modelling. In the last case it is possible to prognosticate the probabilistic duration of the whole process, giving for all activities optimistic, likely and pessimistic evaluation of duration time. Here it is possible to take the probability of iterations, time for reworks and decreasing the learning time into account [9].

At the same time it is obvious that without thorough and detailed research into the human impact or the so-called “bad engineering” it is impossible to evaluate the negative synergy effects in the teamwork and prognosticate the realistic development time. In this case there are two possibilities: to use the company’s own quality disturbances database or to use generalized data collected by the team of authors. However, at first it is necessary to specify the terms used in the further analysis. All shortcomings occurring at the design and launch of the interdisciplinary systems were classified into three main categories: human faults, human mistakes and technical problems. Faults are wrong decisions that have no justification. To the faults’ category belong communication misunderstandings F1 between the client and the design team or between members of the design team. To the second category of faults F2 belong all shortcomings connected with negligence. Faults F1 may be treated as a result of negative synergy in teamwork and F2 as negative synergy in person inner communication. Mistakes are usually caused by the lack of competence M1 or due to unknown matters at the moment of design M2. So the last part of these mistakes can be recovered in a normal set-up process of the automated systems or in further research and they cannot be treated as causal mistakes. A special category here is formed by technical problems where a component is working poorly or does not function at all. If to take out from technical shortcomings the problems caused by aging of materials, wear, etc. these shortcomings seem to be also human-based but belong usually to another company. In Fig 8 there are compared different data on human shortcomings analyzed by our research team during the last dozen years. Such kinds of research results are very rarely published and so for understandable reasons the companies involved are anonymous.

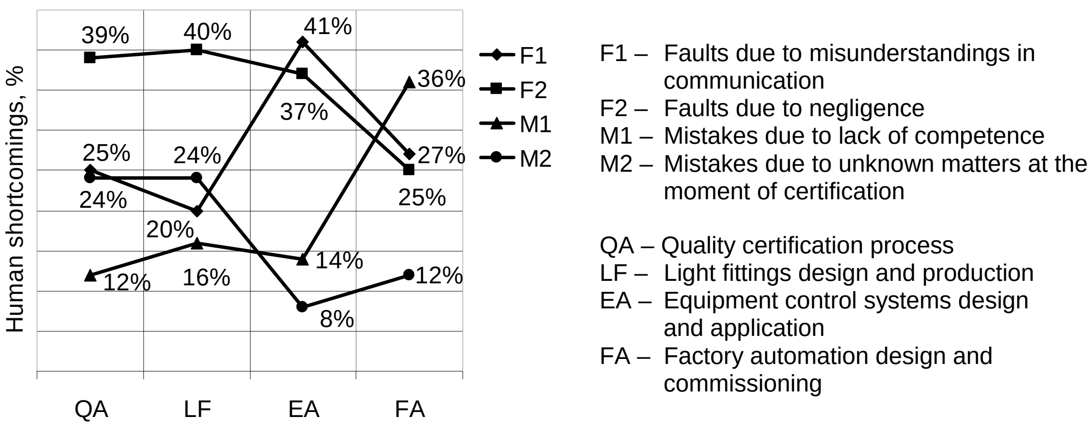

Figure 8. Comparative analysis of human shortcomings

As one can see the spectrum of human shortcomings in quality management is very close to real factory data that leads to the conviction about the universal nature of human shortcomings in a maturity company. However, in the area of equipment control the tasks always vary and work is so strenuous that the share of faults starts to dominate over the mistakes controlled by professionalism. In the more complicated area – factory automation – a lot of standard solutions are available and the share of faults is reducing but the role of mistakes M2 is growing, as the prognosis of the processes character may appear to be wrong for the real conditions.

Block 2 in Fig. 4

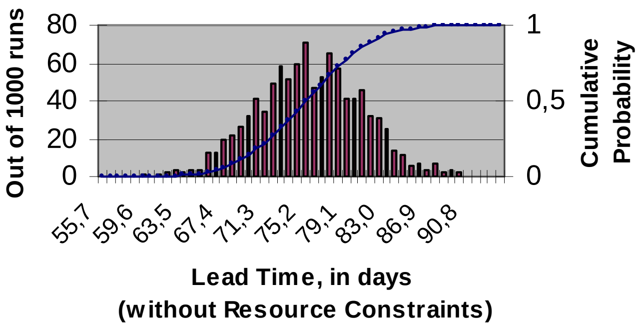

Figure 9. Prognosis of the development time

In Fig. 9 the result of probabilistic analysis of the development time for the activity based market relations matrix (see Fig. 4) is shown. In conclusion it is necessary to say that the key to reducing the negative synergy effects is to increase the synergy of teamwork at the design and application stages and the team's overall core competence.

5 Conclusions

The present paper gives an overview of the complete testing of the synergy-based design methodology of interdisciplinary products provided in real industrial environment. Modern light fittings are a clever integration of mechanical support structure with optics, thermal engineering and electronics. The testing results have been promising and it has shown that the completed methodology is ready for wider industrial use.

As the result of the testing it has been proved that the chosen basis for the design methodology, the Design Structure Matrix technology, enables to describe the synergy interrelations between allied technologies exactly enough. By integrating the Design Structure Matrix technology and the Theory of Design Domains it has been possible to create a generic environment for the design of the interdisciplinary systems on the border of the prescriptive and descriptive design environments. In the above-mentioned environment it has been possible to develop a category of adaptive design tools allowing the synergy-based synthesis of the decision-making algorithm depending on the competence of the design team.

The main value of the proposed approach is the possibility to consider not only the quantitative characteristics of positive and negative synergy of allied technologies at their integration but also market relations and human aspects. The quantitative level of new product synergy is market-driven and for this type of consumer goods it is about 10-15% of the level needed in space and nuclear technology. This level must be assured by quantitative evaluation of synergy between different design parameters on a 3-step scale and by corresponding efforts at synergy-based optimisation of their integration. Human mistakes - competence and expert knowledge - are involved in the process of completing the matrixes. Human faults are taken into account in the prognosis of development time. For the evaluation of human shortcomings a special database was completed in the light fittings company.

It is shown that the present design methodology enables to attain the optimal (market-driven) level of synergy and quality of interdisciplinary products with enhanced functional quality and competitive power. The most difficult here is to obtain ability of synergy-based thinking and use of the integrated synergy-based optimisation technology for the compensation of mutual weaknesses of allied technologies and amplification of their common useful effects to increase positive synergy.

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