INTERNATIONAL CONFERENCE ON ENGINEERING DESIGN, ICED'09
24 - 27 AUGUST 2009, STANFORD UNIVERSITY, STANFORD, CA, USA

A NEW COMPUTER-AIDED APPROACH TO SUPPORT DESIGNERS IN CONCEPTUAL DESIGN OF COMPLEX MECHATRONIC PRODUCTS

Albert Albers[1], Hans-Georg Enkler[1], Markus Frietsch[1] and Christian Sauter[1]
(1) IPEK – Institute of Product Development, University of Karlsruhe (TH)

ABSTRACT
As in every new development of complex mechatronic systems designers have to face several challenges. Especially in system design and conceptual design activities designers often resort to already existing components that are combined and arranged into a new system which has to fulfill a predefined set of requirements. Regarding the humanoid robot ARMAR III of the Collaborative Research Center 588, these components are—amongst others—joints, motors, gears and sensors. Since there is a huge number of catalogues of different manufacturers, especially in multi domain systems, one big challenge is to find an optimal configuration. Furthermore designers have to deal with requirements and constraints that are changing during the development process. This article introduces a new approach to support designers in this task by means of a computer aided approach. General goal is a (semi-)automatic generation of compatible conceptual design proposals that meet the predefined requirements.

Keywords: product development, mechatronics, configuration, conceptual design, optimization

1 INTRODUCTION
During the last two decades the competition has clearly aggravated in many markets. Effects of globalization and therewith the worldwide growing competition led to a dramatic reduction of product lifetime in the market. Companies are forced to shorten the development times of their products and to cut costs while ensuring quality at the same time. The multitude of product recalls of modern automotive products reveals how difficult it is to meet these requirements. Especially the development of complex and multi domain products—such as a humanoid robot ARMAR of Collaborative Research Center 588 (CRC588) [1]—designers have to face several challenges.
An important approach for enterprises to be successful in this contradictory context is to utilize computer aided software tools in product development. The aim is to gather information, e.g., about the product's dynamic behavior during early stages of the development. This helps to avoid expensive and time-consuming failures and iterations in later phases of the development process. Other key factors are methods which support the engineer during the design process. The step from a functional description of a system behavior to the design of its components is a challenging task which can be supported, e.g., by the Contact and Channel Model (C&CM) introduced by Albers and Matthiesen in 2002 [2]. Working Surface Pairs (WSP) as pair-wise interfaces between components and Channel and Support Structures (CSS) as physical components, which connect only two Working Surface Pairs, are basic elements (q.v. section 2) of the model.
Today, use of simulation tools is common practice in many fields of product development to overcome these challenges. Performance and complexity of modern simulation tools and methods increased steadily throughout the past years. Most of these tools can only be applied if the level of detail is relatively high and the level of abstraction is relatively low as in the upper right quadrant of Fig. 1.
But as in new development of complex mechatronic systems designers normally start from a low level of detail and a high abstraction level where there is a lack of tools to support these activities. Especially in system and conceptual design activities designers resort to experience and already existing components that are combined and arranged to a new system which has to fulfill a predefined set of requirements. Soininen et al. define the task 'configuration' as 'the problem of designing a

product using a set of pre-defined components while taking into account a set of restrictions on how the components can be combined' [3]. Since there is a huge number of catalogues of different manufacturers, especially in multi domain systems, one big challenge is to find an optimal configuration. Furthermore designers have to deal with requirements and constraints that are changing during the development process. This article introduces a new approach to support designers in this task by means of a computer aided approach. The General goal is a (semi-)automatic generation of compatible conceptual design proposals that meet the predefined requirements.

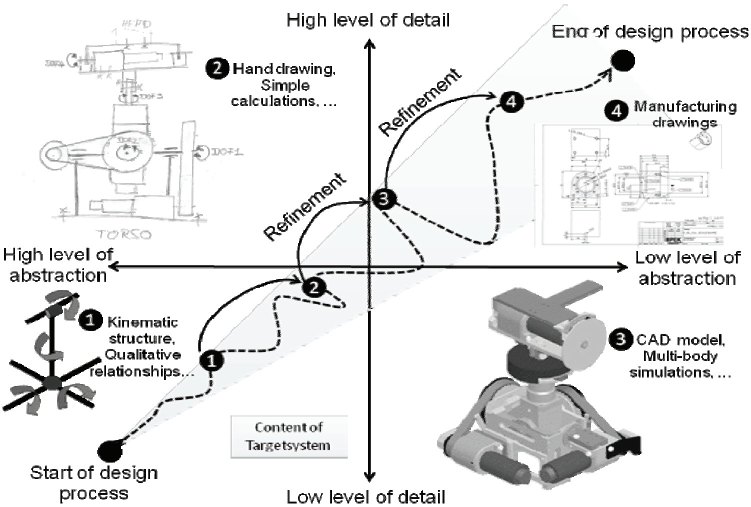

Figure 1. Development of the neck of ARMAR III

2 THE CONTACT AND CHANNEL MODEL

Conventionally engineering products are modeled by components with defined geometry, which are grouped into sub-system and systems. The C&CM approach takes a different way towards geometry, by using Working Surface Pairs, which carry out functions and Channel and Support Structures connecting these working surface pairs. This idea was originally presented by Albers and Matthiesen. It bases on earlier considerations of important design scientists like e.g. Releaux [4], Rodenacker [5], Roth [6], Koller [7], Hubka [8] and others and enlarges these by some important definitions concerning the relations between the basic elements of different technical systems. The experiences of the authors with the description of many technical systems indicate that the concepts defined in the following are sufficient to describe any system with any functionality:

Working Surface Pairs (WSP) are all pair-wise interfaces between components and between a component and its environment. These can be solid surfaces of bodies or boundaries with surfaces of liquids, gases or fields which are in permanent or occasional contact with the Working Surface. They take part in the exchange of energy, material and information within the technical system. Channel and Support Structures (CSS) are physical components or volumes of liquids, gases or spaces containing fields, which connect exactly two Working Surface Pairs. They do not only transfer the system variables energy, material and information from one Working Surface Pair to the other but they can also store them (e.g. inertia). Limiting Surfaces (LS) are surfaces that are not involved in fulfilling the regarded function of a system. But they are potential working surfaces. E.g. the side of a crane pillar only needs to be regarded as a Working Surface, when wind is considered or when it fulfils any other function that the designer has to think about. Remaining Structures (RS) are those volumes of material that do not fulfill any function but are nevertheless part of the system. Examples for Remaining Structures are production-caused parts of a molded housing. Removing them would not change the function of the system but would cause additional costs.

Within the scope of his work on validating drive trains Schyr extended the approach of the C&CM [8]. His aim was to combine the strength of this model in research and education with the simulation language Modelica. The basic concept is to mathematically define the physical properties within Modelica. In this context, Schyr uses so called Behavioral Mock-Ups and enhances the Working Surfaces of the C&CM by the properties of connectors from Modelica. The physical properties of CSS are modeled and described by equations. Furthermore, Schyr shows how typical problems within the validation phase of drive trains can be handled by linking Working Surface Pairs and Channel and Support Structures. As an alternative, he proposes to first generate an abstract model before generating a concrete geometric model in the design phase.

3 A NEW APPROACH FOR COMPUTER AIDED CONCEPTUAL DESIGN

3.1 ARMAR III

The Collaborative Research Center 588 "humanoid robots – learning and cooperating multimodal robots" has the objective of creating a machine that closely cooperates with humans. In this project, scientists from different scientific fields work together to obtain this goal. This development task presents a new challenge to designers. In contrast to industrial robots—for which mechanical rigidity, precision and high velocities are primary requirements—here the key aspects besides anthropomorphism in general are prevention of hazards to users, a motion space that corresponds to that of human beings and a lightweight design. The robot should have humanlike appearance, motion space and dexterity. Additionally, its kinematics should be familiar to the user and its motions predictable to encourage inexperienced persons to interact with the machine. ARMAR III is the humanoid robot of CRC588, cp. Fig. 2. In 2009 and 2010, the next generations of ARMAR will be built. Due to some significant changes in motor and sensor technology this next generation of ARMAR will not be an evolutionary improvement but a completely new development.

Figure 2. Upper body of ARMAR III

3.2 Motivation

New products are often based on a combination and arrangement of already existing components. The new system has to fulfill a predefined set of requirements. Due to the huge number of catalogues of different manufacturers, especially in multi domain systems with a huge number of interdependencies, it is an even bigger challenge to find an optimal configuration. Amongst others this leads to new mechatronic WSPs such as interfaces, protocols, EMC in addition to conventional mechanical WSPs. It is necessary for designers to be at least familiar with the involved domains and their requirements and boundary conditions. Close communication is one of the main factors to avoid suboptimal solutions. Furthermore designers have to deal with requirements and constraints that are changing during the development process. A fast and automated evaluation of the current system design regarding these changes and—if necessary—the derivation of a new system design is desired. The impact of fuzzy requirements and boundary conditions on the 'optimal' system design should also be considered. Finally, a complete and systematic evaluation of possible component configurations even off the beaten track could possibly lead to innovative solutions. Manual exploration of all these aspects is often not possible due to time restrictions in the product development process. Since many evaluations can be performed through structured procedures, e.g. calculation of the center of gravity for a component configuration, an automated computer aided approach seems appropriate.

3.3 State of the art

Nowadays there is a huge number of product catalogues of a multitude of manufacturing firms. Almost every company has its own philosophy to create these catalogues in order to structure its product portfolio in the best way. This leads to the fact, that catalogues of even very similar products often differ significantly from supplier to supplier. Especially in the development process of mechatronic systems, the designers have to manage a lot of different catalogues to select the needed components from multiple domains like motors, controllers, brakes, sensors, gears, etc. Another challenge is to keep 'up-to-date' with the newest products and innovations in the different domains. Additionally there are diverse kinds of catalogues, e.g. book-like ones, CDs or web pages, which all have to be organized in terms of sharing them with colleagues etc. Although each catalogue is intended to help the designer to find the best suitable product as fast as possible, one can find four different 'levels of assistance'. Based on the following example—a drive unit with a required output of 5 Nm—these levels are described below.

Using a level 0 catalogue—often big tomes with the complete product portfolio in one single book, annually updated, with text links to compatible components—will result in a very time consuming process: On the one hand the designer has to look for 5 Nm DC motors, but also for 5 Nm EC motors. On the other hand he has to look for different gears (depending in the selected motors). Additionally new requirements and boundary conditions regarding controllers or sensors can arise by selecting one component. All this has to be taken into account by the designer.

Level 1 catalogues provide comfortable search functionalities and hyperlinks to compatible components. Thus it is faster but not easier for the designer to look for compatible configurations. The bulk of manufacturers' web pages and also most of the product CDs offer these functionalities.

Level 2 catalogues include tools like component filtering to avoid selection of incompatible configurations [11]. The user does not have to look at the text- or hyperlinks to check for compatible components manually. This is done automatically by the software. By choosing one component, the number of possible configurations is reduced to assist the designer in finding the required combination.

All preceding levels are limited to the products of only one particular manufacturer. This is in fact unsurprising because every company aims to distribute their own products. But from a designers point of view a manufacturer spanning solution would be much more auxiliary. A small step towards this goal is already realized in terms of CAD-models.

In [12] a level 3 approach based on a database of over one thousand motors and one thousand transmissions of different manufacturers was implemented. This database contains over ten thousand possible configurations. The designer has to enter the required torque, angular velocity and optional boundary condition (EC motors only, no gears, etc.) and the selection process, based on an automated dimensioning, is executed automatically. This facilitates the selection-process and allows faster reactions in case of changing requirements or boundary conditions.

The remaining disadvantage of this framework is its lack of flexibility regarding additional boundary conditions like design space, EMC, resonance frequencies, dynamics and other multi-domain effects. Therefore additional tools, like CAx- or simulation tools, have to be integrated. Also fuzzy requirements (e.g. 5 Nm +/- 1 Nm) or a weighting of different criteria against each other are not possible in the existing frameworks. Due to the situation described above, efforts in generating a greater support for the development of mechatronic systems have been made e.g. [10].

4 APPROACH

We propose a new level 4 catalogue approach that is divided into two main layers: an automated iterative selection process to generate compatible configurations and an optimization layer. The first layer is based on the 'conceptual verification' method developed at the IPEK and presented in [13] and [14]. The paper extends this manual method to a computer aided process, which supports the designer in creating a system that meets the requirements (design space, efficiency factors, EMC, etc.) in an optimal way. The second layer supports the designer in the following optimization, or rather, evaluation step. Therefore an interaction-process of this catalogue with the CAD software ProEngineer (as a sample for any kind of CAx software) is presented. The whole framework aims not to replace the human designer but to assist the designer in time-consuming and simple tasks in order to gain more time for the creative part of his work, which cannot be transferred to a computer.

4.1 Iterative selection process using threshold based parameters

When designing complex new systems, the design task is commonly segmented into smaller subtasks resp. subsystems. For complex mechatronic systems a segmentation based on the functional structure like proposed in [15] is recommended. Using the example of the humanoid robot, the subsystems are joint complexes like elbow or shoulder joints. The objective of the first layer is the generation of compatible design proposals for these subsystems. In order to create these proposals a universal component library is necessary. This library has to contain all component specific information like engine speed, torque, efficiency factors, CAD data (design space, CAD-model, etc.) but also metadata like type of motor, compatibility parameters or level of preference for a specific component or manufacturer etc. This data can be easily accessed by using an MS Excel sheet, cp. Fig. 3. By means of this user friendly maintenance of the product portfolio used in the later process is guaranteed. To allow easy exchange and update of this library, a standardized file format is necessary. We use a XML, cp. Fig 4, firstly because it is very well suited for this application (easy extendable, easy readable etc.) and secondly because it is already an established standard [10].

manufacturer	product id	torque	efficiency factor	dimension x	dimension y	dimension z	diameter	voltage
SEW	S/00102	10	0.91	45	90	177	4	24
SEW	S/00103	15	0.91	35	85	185	6	12
SEW	S/00104	20	0.89	34	93	105	6	12
SEW	S/00105	25	0.90	33	81	100	11	12
SEW	S/00106	30	0.85	31	99	193	12	24
SEW	S/00107	35	0.92	31	100	184	5	12
SEW	S/00108	40	0.93	35	84	106	6	12
Maxon	m-33541	35	0.82	31	85	178	10	24
Maxon	m-33542	20	0.86	45	88	137	8	12
Maxon	m-33543	15	0.85	32	100	150	2	12
Maxon	m-33544	10	0.87	38	94	181	10	24
Faulhaber	F14235	20	0.83	30	86	194	4	12
Faulhaber	F14236	23	0.79	32	94	137	9	12
Faulhaber	F14237	27	0.81	42	99	192	5	12
Faulhaber	F14238	32	0.81	31	95	175	7	12
Parker	512p	15	0.81	40	100	187	7	12
Parker	513p	12	0.76	43	87	196	5	12

Figure 3. User friendly maintenance of product portfolio

```
<index>
    <title>electric motor DC</title>
     <item>
        <keyword>manufacturer</keyword >
        <text>SEW</text>
     </item>
     <item>
        < keyword >torque</ keyword >
        <text>10</text>
     </item>
     …
</index>
```

Figure 4. Example for entry in XML-based component library

Based on this component library the selection process is performed using various requirements and boundary conditions. In contrast to the already existing level 3 solution, the user has easy access to every property of the components. Therefore a multitude of various criteria can be tested and taken into account when generating design proposals. Thus it is also possible to include component properties like electric motor parameters, inertia, etc. into other software, to determine parameters that do not exist in the components parameter list yet. The main advantage is the possibility to do so with complete compatible solutions. The catalogue framework can e.g. automatically simulate the dynamic behaviour of a drive unit using Matlab/Simulink and reject this configuration, if the starting current

exceeds a given limit. To generate compatible configurations that meet the requirements and boundary conditions, several steps are executed: Firstly the total number of possible configurations has to be reduced by eliminating the component combinations that do not lead to feasible configurations. This is done by using a system hierarchy as depicted in Fig. 4. If looking for an electric drive unit for example, only electric components were selected. Secondly 'don't-like' components were eliminated to realize company specific preferences. Thirdly components with parameters outside a specific range were eliminated as well. E.g. if there is an efficiency requirement of 70% all components with $\eta<70\%$ were eliminated. Other methods to accelerate the search process like saving old results etc. are imaginable.
After the search space has been reduced as much as possible, the generation of compatible configurations is performed. This is done by creating all possible combinations of e.g. motors and gears following the product hierarchy depicted in Fig. 5. Every potential solution consists of 'component primitives' (P_1, P_2 to P_n), that are combined using an own library for each primitive. These libraries also contain 'zero-elements' to cover components, that are no necessarily needed for a solution (e.g. in case of a bigger motor no transmission element might be needed). The integration of CAD-models into the library data is beneficial in different manners. They can be used either for the selection process or for the later optimization resp. evaluation step.

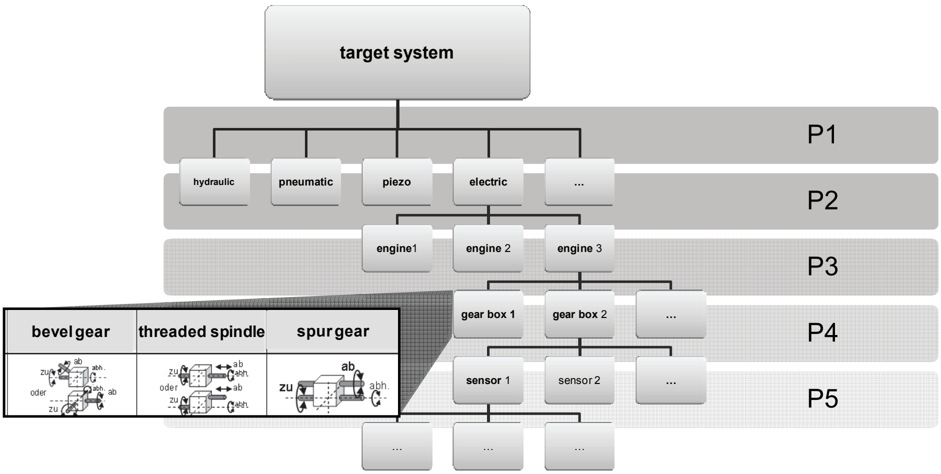

Figure 5. Possible hierarchy of a system configuration

Additionally the designer does not have to look for each single CAD-model, if a configuration is chosen at the end of the process. Within the selection process, the CAD-models can be used for a multitude of analysis e.g. design space or centre of gravity. For correct assembly of single components in the CAD environment an approach based on the C&CM model described above is used. Each component has to be provided with working surfaces for connecting them to each other and to a possibly existing environment. In Fig. 6 an early concept of the third degree of freedom (DOF) for bending the robots elbow can be seen. The upper arm and the forearm, which are not shown, will be mounted above resp. below. On the left half an invalid configuration with a motor exceeding the design space can be seen. The design proposal on the right side fits into the given space and is retained for further steps. At the moment this time consuming step must be performed by hand.
Additionally a new concept of 'mechatronic WSPs' is used to determine the validity of design proposals. This concept extends the conventional WSPs presented in [2] to a more general approach for mechatronic systems. The basic idea is that both physical elements e.g. connectors (type of connector, number of pins etc.) but also non-hardware elements like bus-protocols (Can-bus, FlexRay etc.) can be seen as working surfaces. If combining two components into one system, both working surfaces have to be present in order to generate a valid design proposal. E.g. an angular sensor for measuring the orientation of an EC-motor must be able to communicate with the motor controller, therefore the same interface (Working Surface) is needed on both sides. To realize the integration of fuzzy or indistinct requirements, thresholds and ranges are used. All combinations are evaluated using

different methods, as mentioned above, to determine proposals that fulfil the requirements. The evaluation is accomplished iteratively for each single criterion to steadily reduce the number of possible solutions. The evaluation methods vary strongly in their computing time e.g. performing

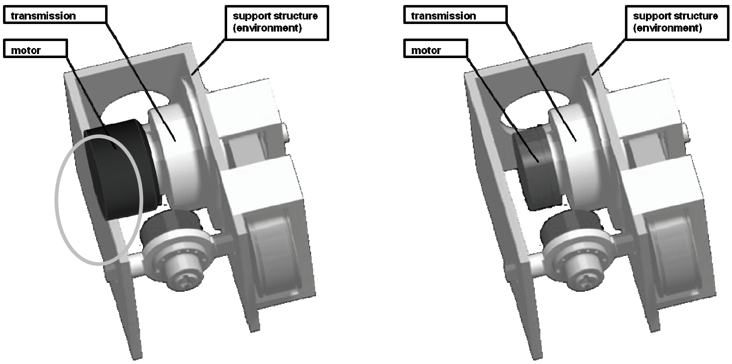

Figure 6. Rejected (left) and accepted (right) design proposals of elbow joint

analysis that involve external software, like CAD or simulation tools, requires significantly more time than a simple threshold check. Therefore the less time consuming tests should be performed firstly to reduce the total number of combinations for the subsequent evaluation steps. Hence the optimal sequence regarding the computing time of those tests will be evaluated automatically in the future. The output of this process are several different design proposals that fulfil the requirements. By creating a target function containing the fulfilment level of each criterion, a customized weighting of the different requirements can be realized. E.g. weighting design space or weight against torque to get more suitable solutions. The final design proposals are further optimized by the optimization layer as described in the next section. Initially it is a relatively time intensive process to collect all relevant datasets and to feed them into the database. Firstly this has to be done only once resp. for new data only and the longer the catalogue is used, the bigger is the benefit of this framework. Secondly the long term goal is to establish a catalogue system similar to the BibTex-system, which is a standard in publishing references. Each company could provide their catalogues also as downloadable XML-versions to facilitate it for the user to keep its own library up to date. Also an automated library update, similar to a virus scanner, is imaginable. This concept offers also big advantages to manufacturers: a fast distribution of a new product, resp. the knowledge that a new product is available, without having to wait for the new printed catalogue.

4.2 Optimization of the component configuration

After having generated a set of compatible component configurations it is necessary to spatially arrange the components, i.e. to define position and orientation. During this process several restrictions such as design space, electromagnetic compatibility, etc. have to be taken into account. During the development of ARMAR III this locating process had to be done in the torso as well as in the locomotion platform of the robot. There were many different components like drive units for the elbows, motor-controllers, PCs, WLAN, etc. that had to be located in an optimal way regarding the position of the centre of gravity and other boundary conditions. The resulting torso can be seen in Fig. 7. As this positioning process was very time consuming, an automated approach for the development of ARMAR IV is desired.

In order to provide this automated process, we propose an integrated approach using a combination of CAD, CAx and genetic algorithms.

Genetic algorithms (GAs) are adaptive heuristic search algorithms (stochastic search techniques) based on the ideas of evolutionary natural selection and genetics [16]. There exist several free and commercial software implementations—such as DAKOTA (Design Analysis Kit for Optimization

Applications) developed at Sandia Laboratories [17, 18]. DAKOTA is an optimization framework with the original goal of providing a common set of optimization algorithms for engineers who need to solve structural and design problems. In order to integrate CAD, CAx and DAKOTA, it is necessary to develop an interface to link the GAs to the CAD models of the components chosen in the iterative

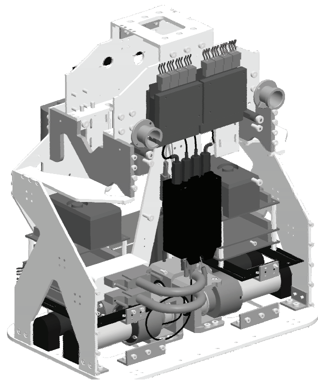

Figure 7. Torso of ARMAR III

selection process described above and—if necessary—to further CAx analysis tools. Due to its good controllability by means of Java, PTC Pro/Engineer [19] is used as CAD software. During the process, parameterized CAD models related to the respective components are loaded, assembled and located using a set of parameters. Subsequently, the configuration is analyzed by Pro/Engineer with respect to available space, collisions, etc. In general, system configurations can be evaluated in many respects. Parameters for locating the components are generated by means of DAKOTA. Data between Pro/Engineer and DAKOTA are exchanged using small ASCII files including a new set of parameters for Pro/Engineer or evaluation results for DAKOTA. The optimization is predefined using an input file for DAKOTA. Pre- and post processing is done by a separate Perl script that is executed by DAKOTA. The implemented sequence of steps is shown in Fig. 8. It depicts the parallel execution of Pro/Engineer and DAKOTA. Due to its high flexibility, the user may integrate additional analyses such as FEA. Further information on the implementation and a detailed example can be found in [20].

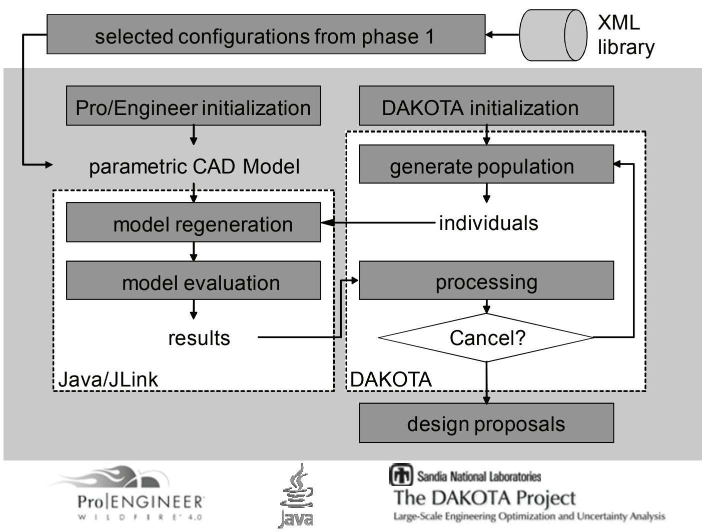

Figure 8. Integration of DAKOTA and Pro/Engineer

The second layer complements the first one: While the first layer provides compatible configurations these configurations are evaluated in detail in the second layer.

5 SUMMARY AND FUTURE WORK

The success of a company strongly depends on speed and capacity for innovation in product development. This article introduced a novel method to support designers in conceptual design phase by means of a computer aided approach. General goal of this framework is a (semi-)automatic generation of compatible conceptual design proposals that meet the predefined requirements. Currently, the presented method is being implemented in a software tool. The method will be evaluated during the development process of the ARMAR IV and V. Furthermore, it will be validated by means of chosen other demonstrators of the IPEK. This will include extending the current elementary component library. On the one hand this extension will be done regarding components of one class (motors, sensors, etc.) and on the other hand by adding new component classes (couplings, brakes, etc.). It is also intended to integrate C&CM, detailed CAD models of manufacturers to enhance accuracy of design space analyses, masses, etc. Besides CAD models, a connection to CAx tools such as Multi Body Simulation or Finite Element Solvers to improve analysis capabilities is possible. Due to performance reasons a further goal is to feed back knowledge acquired in former development processes.

ACKNOWLEDGMENTS

We are grateful for the support of the DFG (Deutsche Forschungsgemeinschaft) within the Collaborative Research Centers 499 ‘Micro Molding’ and 588 ‘Humanoid Robots’.

REFERENCES

[1] DFG Collaborative Research Center 588 “Humanoid Robots – Learning and Cooperating Multimodal Robots”, http://www.sfb588.uni-karlsruhe.de/
[2] Albers, A. and Matthiesen, S.: Konstruktionsmethodisches Grundmodell zum Zusammenhang von Gestalt und Funktion technischer Systeme – Das Elementmodell Wirkflächenpaare & Leitstützstrukturen zur Analyse und Synthese technischer Systeme. Konstruktion – Zeitschrift für Produktentwicklung 54 (2002) 55-60
[3] Soininen, T., Tiihonen, J., Mannisto, T. and Sulonen, R. Towards a general ontology of configuration. Artificial Intelligence for Engineering Design, Analysis and Manufacturing 12 (1998) 357-372
[4] Releaux, F. and Moll, C.: Konstruktionslehre für den Maschinenbau. Vieweg, Braunschweig (1854)
[5] Rodenacker, W. G.: Methodisches Konstruieren. Springer, Berlin (1991)
[6] Roth, K.: Konstruieren mit Konstruktionskatalogen. Springer, Berlin (1994)
[7] Koller, R.: Konstruktionsmethode für den Maschinen-, Geräte- und Apparatebau. Springer-Verlag, Berlin (1998)
[8] Hubka, V. „Theorie technischer Systeme“, Springer, Berlin (1984)
[9] Schyr, C.: Modellbasierte Methoden für die Validierungsphase im Produktentwicklungsprozess mechatronischer Systeme am Beispiel der Antriebsstrangentwicklung. Karlsruhe, Universität (TH), Dissertation (2006)
[10] Devanathan, S.; Ramani, K.: Combining constraint satisfaction and non-linear optimization to enable configuration driven design. International Conference on Engineering Design ICED (2007)
[11] http://shop.maxonmotor.com/ishop/app?language=en&country=INT
[12] http://www.specamotor.com
[13] Brudniok, S.: Methodische Entwicklung hochintegrierter mechatronischer Systeme am Beispiel eines humanoiden Roboters. Karlsruhe, Universität (TH), Dissertation (2007)
[14] Methodische Entwicklung von hochintegrierten mechatronischen Systemen am Beispiel eines Humanoiden Roboters. VDI-Tagung „Mechatronik-Innovative Produktentwicklung“ (2007)
[15] Albers, A.; Brudniok, S.: Development of the highly integrated mechatronical systems of Humanoid Robots, The 17th International DAAAM Symposium "Intelligent Manufacturing & Automation: Focus on Mechatronics & Robotics" (2006)
[16] Goldberg, D.E.: Genetic Algorithms in Search, Optimization and Machine Learning, USA:

Wesley Longman Publishing Co., Inc. (1989)
[17] http://www.cs.sandia.gov/DAKOTA/packages.html
[18] Eldred, M. et al.: DAKOTA, A Multilevel Parallel Object-Oriented Framework for Design Optimization, Parameter Estimation, Uncertainty Quantification, and Sensitivity Analysis. Version 3.0 Reference Manual, http://citeseer.ist.psu.edu/392384.html
[19] http://www.ptc.com/products/proengineer/
[20] Albers, A.; Leon, N.; Aguayo, H.; Maier, T.: Multi-objective system optimization of engine crankshafts using an integration approach, ASME (2008), Boston, USA

Contact:	o. Prof. Dr.-Ing. Dr. h. c. Albert Albers
Institution/University	University of Karlsruhe (TH)
Department	IPEK – Institute of Product Development
Street	Kaiserstraße 10
Postal Code, City	76131 Karlsruhe
Country	Germany
Phone	+49 (721) 608-2371
Fax	+49 (721) 608-6055
E-mail Address	albers@ipek.uni-karlsruhe.de
URL	http://www.ipek.uni-karlsruhe.de

Albert Albers, born 1957, is full professor of the IPEK – Institute of Product Development at the University of Karlsruhe. After working as head of development of coupling systems and torsion vibration dampers at LuK GmbH & Co. OHG he changed to IPEK in 1996. His research focuses on models for product development processes as well as the support of product development by methods for computer aided engineering, innovation and knowledge management in mechanical and automotive engineering. Hans-Georg Enkler, Markus Frietsch and Christian Sauter are academic assistants at the IPEK.