Development of a Robot for Biomass Handling in a Solar Greenhouse Dryer

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ABSTRACT

Solar and solar assisted dryers for sewage sludge have shown to be a commercially viable alternative compared to conventional drying processes. Therefore, a cost-efficient mixing and transporting robot for processing and handling of various biomass during a solar drying process was developed. To ascertain a systematic and efficient design procedure, the discursive design method VDI 2221 and innovative Computer Aided Engineering (CAE) software tools were used. The analysis of the complex technical system was based on several function structure plans. The derived technical solutions were organised on a morphological chart. The computed technical value (x_A=0.76) and the economical value (y_A=0.77) of the robot testified a high-grade design concept. First drying experiments with the prototype demonstrate the general functionality and applicability. Hence, the combination of the VDI design method with specific CAE-tools is suitable for reducing the development period on the innovation driven market of biomass processing.

Keywords: Systematic design, engineering, robot, biomass, residuals, sludge, drying, solar.

1. INTRODUCTION

In many agricultural, communal and industrial processes moist biomass such as sludge from biogas plants and waste water treatment plants or by-products of food processing is generated in large quantities. Removing water from those materials is necessary to reduce transport and storage costs, increase the calorific value, improve the biological stability or concentrate the nutrients when being used as fertilizer. Furthermore, handling and storage are simplified and new fields of beneficial applications such as energy generation are opened. Due to the low market value of biomass and the high thermal and electrical energy requirement for drying, conventional processes are not viable in many cases. By using solar assisted driers the initial mass of sewage sludge can be reduced to approximately 33%. The entire required electrical energy for the whole procedure is about 30 kWh per ton of evaporated water (Bux and Starcevic, 2005). In this respect, solar and solar assisted dryers have shown to be an interesting and commercially viable alternative to conventional drying processes (Bux and Baumann, 2003). Currently, most of the solar-based technologies are only suitable for relatively homogenous wastewater sludge. However, there is a much wider range of biomass available such as communal biowaste, wood chips or effluents from biogas plants. But no automated technologies are available for loading, mixing and unloading of such heterogeneous drying materials. Therefore, those operations are labour intensive and burden the economy of solar biomass drying. In current research, manual labour in greenhouses has been replaced by robotics (Belforte et al. 2006). However, those robots have been developed for sophisticated operations like harvesting or plant manipulation and are not suitable for biomass handling (Van Henten et al. 2006, Cho et al. 2002). At the same time, different methods of reducing the manufacturing and running costs of agricultural systems have to be extended (Reid et al. 2003). Therefore, objective of joint research of the University of Hohenheim and industrial companies (Thermo-System, Germany; ACAT, Austria) was to develop a cost-efficient robot for loading, mixing and unloading of biomass in a solar greenhouse dryer. The idea of that mixing robot was patented (Bux et al. 2003). A further objective was to investigate suitability of a systematic design method to integrate ideas and preferences of all involved parties in a transparent manner.

2. METHODS

To ascertain a systematic design procedure, the discursive design method according to directive VDI 2221 et sqq. was selected (VDI 2221, 1993). The directive divides the engineering process into seven fundamental working steps. Depending on the problem for each of these steps, several specific methods are recommended. The steps and the referring results are shown in Figure 1.

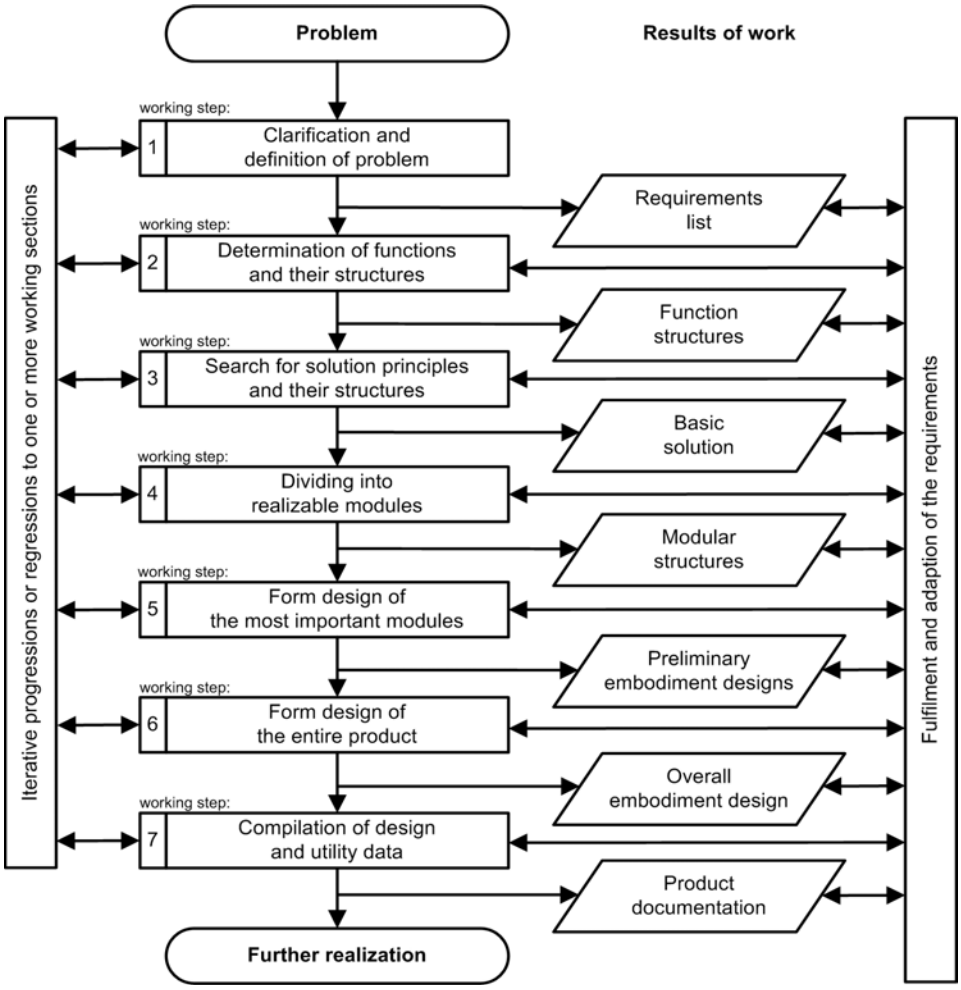

Figure 1. General VDI-procedure of systematic development and design (VDI 2221, 1993).

For step one, the "searching matrix" method proposed by Roth (Roth, 1994) was used, resulting in several detailed requirement lists. For step two, directive VDI 2222 was selected

(VDI 2222, 1997). For step three the method of VDI-engineering morphology was used (VDI 2222, 1997). Referring to Pahl/Beitz (Pahl et. al., 2005) an own pre-evaluation method was developed. Applying the pre-evaluation method, the principle solutions were combined to two promising general concepts. These were constructed in step four and five. Then these two competing preliminary embodiment designs were evaluated by using technical and economical aspects according to Kesselring and VDI-directive “Technisch-wirtschaftliches Konstruieren” (VDI 2225, 1998; VDI 2223, 2004; VDI 2222, 1982). The best design was selected and finalised in step six. The engineering software CATIA, Dassault Systems, was used for the 3D-design, the finite-elements-method structure analysis, the assembling simulation and the simulation of kinematics including collision check.

3. RESULTS AND DISCUSSION

3.1 Requirements and Functional Basis of the Robot

The “searching matrix” resulted in several detailed requirements lists (not shown). The requirements on the various functions were abstracted and set up in an overall function structure plan for the “Biomass Manager”. The main-functions of the overall function structure plan are represented by four more detailed sub-function structure plans, “movement in x-y-direction”, “movement in z-direction”, “mixing” and “distributing”. Figure 2 shows the simplified overall function structure plan, including the main-functions of the product. The function structure plan shows the energy, signal and material flows that are required to fulfil the function. Furthermore, Figure 2 shows, as an example for one of the four detailed sub-function structure plans, the sub-function structure plan for the main-function “moving tool retainer in z-direction”. Hence, the model for the construction of the entire machine is multidimensional. Regarding the flows in the sub-function structure plan, moving the tool retainer in z-direction can be realized as follows: 1.) Energy has to be converted to receive power. 2.) The power has to be transmitted to the point of load incidence. 3.) Energy reflux has to be locked to make sure that the orientation of the power is correct. 4.) The tool retainer has to be lifted, lowered or pushed. 5.) The displacement has to be guided securely to guarantee the proper direction of movement. 6.) In addition, the forces have to be transferred into the main beam and into the ground respectively. Thus, the balance of forces is reached. 7.) Finally, the movement of the lifting device has to generate the movement of the mixing and transporting tool by several kinematic principles. As result of the sub-function structure plan, the mass flow is located at the final state and the tool reached to the intended new z-position. As exemplarily shown for the main-function “moving tool retainer in z-direction”, each main-function was segmented into at least one sub-function structure plan. Thus, an abstract code for the description of the “Biomass-Manager” was created (Stone and Wood, 2000). This verb form code was the basis for the further search for principal technical solutions using physical working principles and the software tool CATIA Product Function Optimizer.

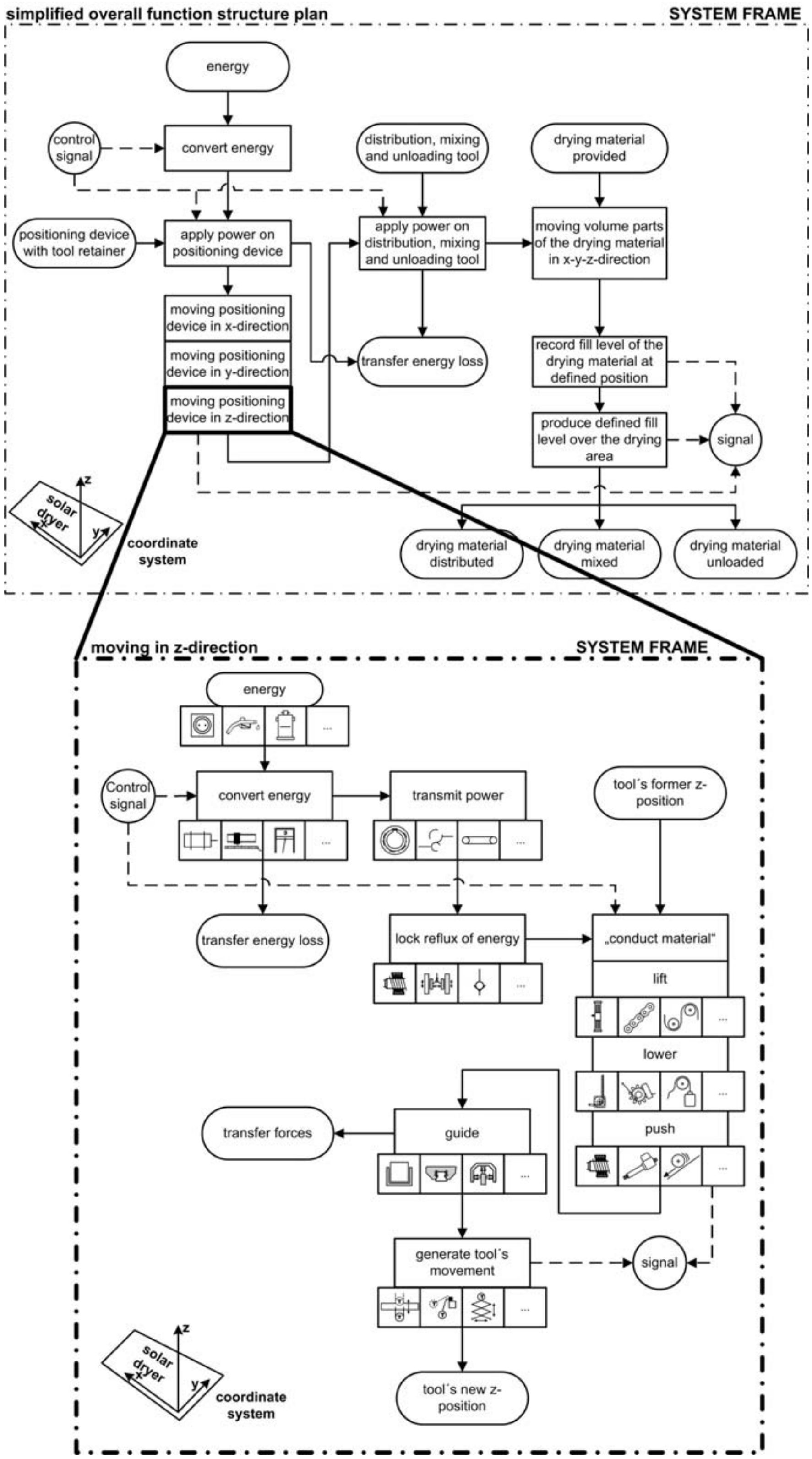

Figure 2. Above: simplified overall function structure plan of the mixing and conveying robot. Below: one of several sub-function structure plans exemplified for the function "moving tool retainer in z-direction". The sub-function structure plan includes several pictograms representing possible implementation options for solving each sub-function.

3.2 Concept Design and Concept Pre-Evaluation

The several function structure plans were organized as morphological charts. For each sub-function, a number of possible solutions were found. The sub-function structure plan “moving in z-direction”, which is shown in Figure 2, includes exemplarily some possible implementation options for solving each sub-function. In order to select only reliable and cost-efficient components, a pre-evaluation matrix was created (not shown). Each of the found 154 implementation options was pre-evaluated according to five selection criteria: 1.) Function fulfilment and operational reliability. 2.) Investment and implementation costs. 3.) Maintenance and servicing costs. 4.) Design and optical quality. 5.) Positive self-made experiences. For each sub-function, exclusively the best ranked components were chosen. These components were combined with each other to two basic functional working structures A and B. Figure 3 shows the preferred implementation solutions for each sub-function of the two competing alternative solutions A and B. These two most promising solutions were worked out and each component was pre-dimensioned and engineered.

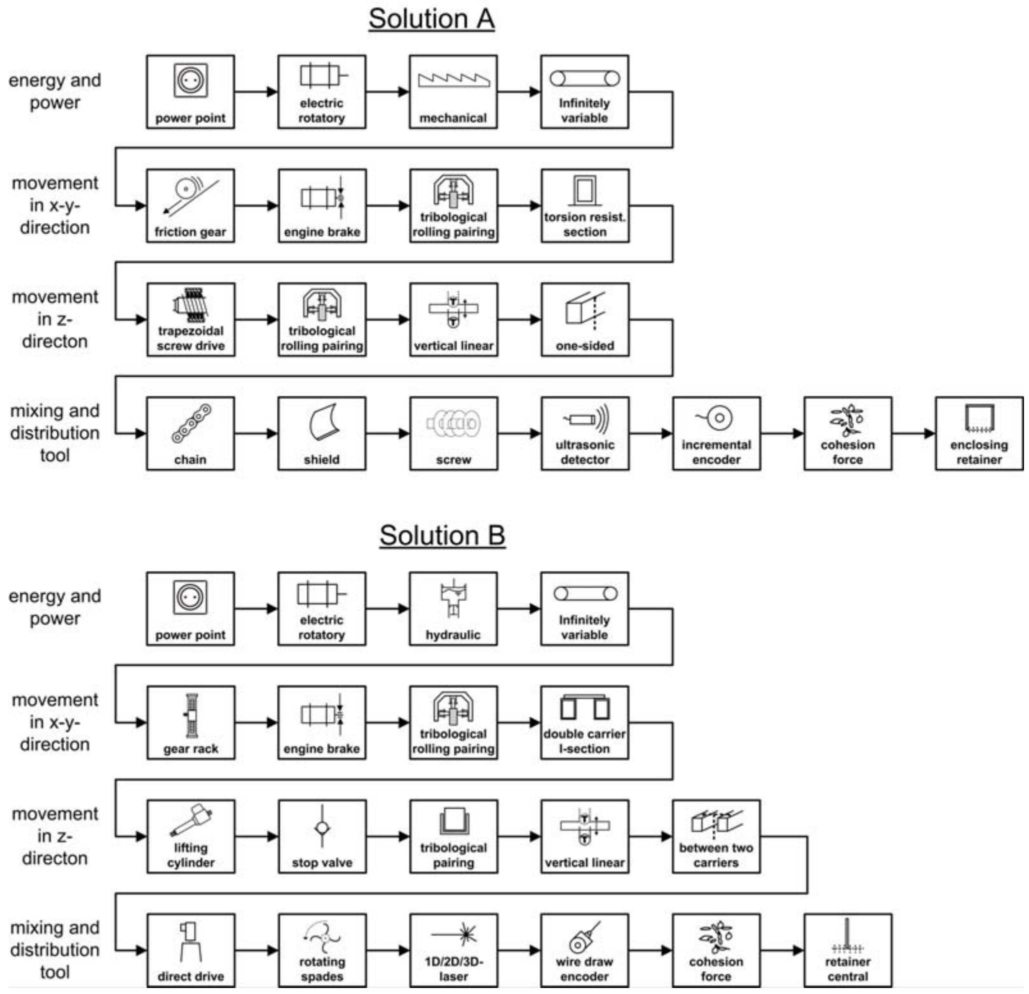

Figure 3. Preferred implementation solutions for each sub-function of the two solutions for the robot.

3.3 Technical and Economical Evaluation to Estimate the Best Concept

For a comparison of the two engineered solutions with state-of-the-art solutions, the VDI technical-economical evaluation method was applied as shown in Figure 4. The technical average grade of option A was x_A=0.76 and x_B=0.82 for option B. The referring economical values are y_A=0.77 and y_B=0.65 respectively. The computed VDI "product strength" s_i of the alternatives is s_A=0.8 and s_B=0.7. Other State-of-the-art mixing devices were also technically evaluated (Company I-III). Their technical grade referring to the requirements lists is drawn in Figure 4. Both new solutions A and B are characterized by a significantly higher product strength compared to the existing systems. Due to the lower production costs, option A was selected for the production and testing of a prototype.

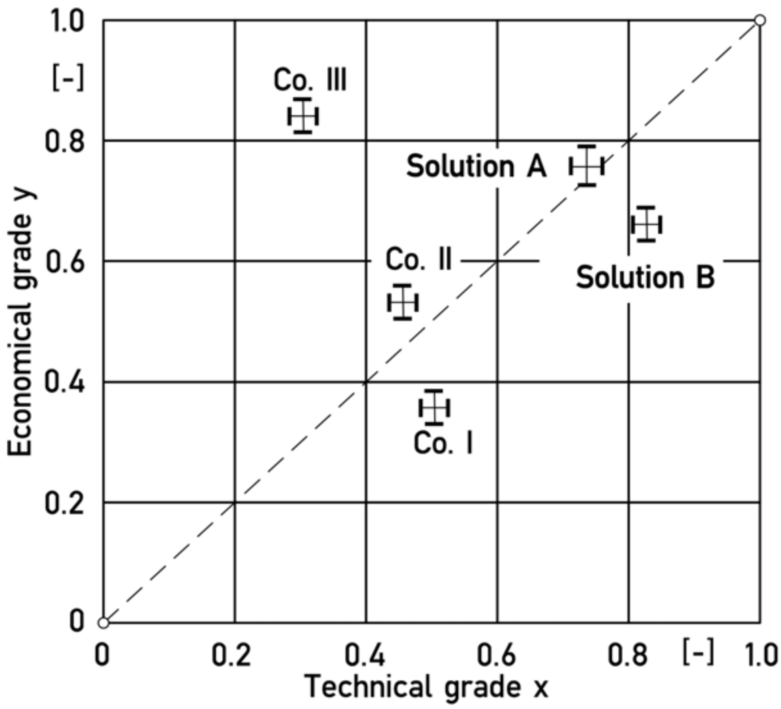

Figure 4. Strength chart of the competing technical solutions compared to state-of-the-art solutions.

3.4 Drives and Sensors Set-Up for the Initial Experimental Runs

Following step six of the VDI design procedure, the first prototype of the autonomous mixing and transporting robot was manufactured and tested as shown in Figure 5. First drying experiments demonstrate the general functionality and applicability. Its forward speed in x-direction is continuously variable up to 30 m/min. The process speed in y-direction is 10 m/min. The rotational speed of the mixing and transporting screw is continuously variable up to 65 rpm. The height of the drying material is continuously monitored by several ultrasonic sensors. A high-precision displacement measurement system continuously monitors the x, y and z-coordinates of the robot position. The coordinates are sent to the main controller to compute the next operations. Via internet file transfer protocol (FTP), it is possible to observe and adjust the current machine parameters such as torque, power requirements of the motors, actual speed and revolution.

The actual status of the control software allows a fully automatic drying process with material mixing in batch or continuous mode.

Figure 5. Prototype of the “Biomass-Manager” during an experiment in a solar greenhouse type dryer. The robot is processing a biowaste-paper blend.

4. CONCLUSIONS AND OUTLOOK

The applied methods of VDI systematic design in combination with high-end computer-aided-engineering software have proven to facilitate an objective and impartial development of a new robot for automatically loading, mixing and unloading of biomass in a solar drying plant. The seven-step VDI design procedure divided the design process into clear working packages. In combination with the searching matrix method initial demands on the robot were systematically developed, resulting in requirements lists. The creation of function structure plans enabled the unbiased search for principal solutions and working principles. These principles were organised in morphological charts which induced further creative technical solutions. By pre-evaluating these solutions, the decision process was made transparent. The subsequent technical-economically evaluation of the preliminary embodiment design ascertained a high-quality design.

During the first experiments the prototype of the “Biomass-Manager” proved to be highly flexible and well suited for the intended application. According to a technical-economical evaluation, the current construction of the “Biomass-Manager” is supposed to be highly competitive to state-of-the-art solutions in the market. Thus, it can increase the competitiveness of solar drying to conventional drying processes and therefore contribute to the protection of the environment. Hence, the combination of the VDI design method and specific CAE-tools demonstrated to be a recommendable design tool for the innovation driven market of biomass processing.

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