From Concept to Specification Maintaining Early Design Intent

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Abstract Early design intent can be compromised as decisions transition in the design process from early concepts to prototyping and to the final specification. This paper presents a method to support designers in the decision making process in the design of innovative products. Bearing selection in kinetic design is used to demonstrate how implementation decisions made in the late stages can heavily impact the early design intent. An inductive research approach is adopted to analyze a collection of existing kinetic products with rotational joints across scales and domains. The resulting macroscopic decision trees demonstrate a way towards a new type of support systems that can be applied at the earliest stage of functional prototyping. An industry case is used to validate this two-stage knowledge schema representation. This method is viewed as a foundational step towards the development of future knowledge-based systems that help teams across disciplines develop creative solutions and maintain early design intent.

Keywords Knowledge representation · Design process · Kinetic design · Kansei

1 Introduction

In the new product development (NPD) process, design decisions are made -sequentially or concurrently- by professionals across various fields of expertise. Design intent refers to the reasoning behind decisions throughout the NPD process. In particular, early design intent is a key element of the 'fuzzy front end' [1, 2]. In industries such as consumer appliances, product designers often make early decisions on the look and feel, where these intentions may remain implicit or only

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partially specified in the design documentation. As a result, the design intent is often compromised in the chain of decisions, leading to innovativeness and implementation shortcomings [3]. This information loss is particularly noticeable in areas such as kinetic design, i.e., where the movement of components in an assembly is an important functional and aesthetic product feature [4, 5]. Kinetic design is susceptible to significant changes to early design intent largely because of a lack of appropriate means to capture the qualitative specifications of movement, i.e., it is problematic to document the intent of 'sturdy elegant' motion when transitioning from conceptual to engineering design. This paper presents a method to bridge the decision making processes across early and late phase design areas. We do this by capturing the concrete late phase requirements in a scalable representation that is sufficiently unconstrained that early upstream decisions can incorporate and resolve. In particular, it is necessary to represent both the physics and the emotive features in the representation. This early resolution allows late phase requirements to be sufficiently incorporated to prevent later compromise of the difficult to capture design intent. As demonstration, bearing selection in kinetic design is taken as our case study to demonstrate how implementation decisions made in the late stages can heavily impact the early design intent. We thereby also show how capturing the myriad of alternative bearing selections early mitigates this effect.

Early design intent refers in this paper to the underlying goals beneath the specification of a design in the early stages of the NPD process where design concepts are initially formed, information is incomplete and representations are ambiguous [1, 2]. In some instances, maintaining early design intent can be achieved via technical documentation where materials and components can be unambiguously specified in engineering drawings. However, when a product is conceived with complex qualitative or sensorial criteria in mind, such as aesthetic features or for certain tactile or proprioceptive modalities, maintaining design intent from the early stages of product conceptualization to final specification remains an open challenge [3, 4]. This paper describes a proposed method to maintain design intent across design areas.

2 Background

Capturing the reasoning behind design components or attributes has been an active area of research [6]. Systems such as Design Rationale Capture illustrate the efforts to extract and use computer-interpretable rationale in engineering design teams [7]. Such systems typically consist of data capturing, representation and retrieval via coupled computer-aided design systems. Data capture consists of knowledge recording which involves encoding as much raw information as possible behind design decisions and representing it in a relevant schema, and design rationale construction which includes the processing and organization of such knowledge [8].

Thus, central to a design rationale system is the knowledge representation framework or schema. The work presented here develops an approach to capture early design intent in domains where decisions span across multiple knowledge schemas.

2.1 Design Decisions

New product development (NPD) is characterized by models including a variety of 'stage-gate' processes [1, 2]. NPD decisions are made *about* different aspects of a product across design stages. Moreover, *how* this reasoning is made differs significantly between stages. Early decisions are often partial and preliminary as they are made with incomplete and unstructured information and in the face of ambiguity and uncertainty. In later stages, as information and feedback about appearance and function is available from prototypes, decisions become more definite, comprehensive and in depth. Several studies have captured the differences in decision-making between product and engineering designers [9].

This work focuses on the transition between the concept design stage where initial decisions are usually made by industrial or product designers, and the early implementation stages of engineering design [2]. It is in this transition that early design intent is transferred across disciplinary areas in a process that is critical for developing the final product while maintaining its originally intended character. We view this handover as a creative process that remains largely unrecognized, poorly understood, insufficiently addressed in education and largely unsupported in professional practice.

The process of transferring design intent across stages can be a major source of conflict in teams where innovative products are developed starting with an original concept and finalizing with a comprehensive design specification. Design representations used by industrial design and engineering design professionals such as models and prototypes support different decision-making processes [10]. Industrial design models tend to be exploratory and built as block models or simple moving parts to capture appearance, use and ergonomic factors. Engineering design models comprise functional, assembly, and production models with limited or no reference to the intended appearance. Because each design area develops an array of representations to generate, develop and test their own priorities, it is apparent why conflicts may arise in the transfer of decisions.

2.2 Kinetic Design

To illustrate our conceptual approach, we select kinetic design as an exemplary area where design intent includes complex multi-sensorial factors. Kinetic design refers to the design of consumer products with movable components, particularly those where movement is a primary design feature. Examples range from doors to advanced robotic products. In such products, the “semantics of movement” or “language of motion” [4, 5] is envisioned -albeit challenging to articulate objectively- in the conceptual stage, and is difficult to translate into the selection of mechanisms that embody the aesthetic intention.

Beyond the particular case of kinetic products, this approach is applicable to the design of innovative products in general where the integration of desirability and feasibility criteria is important. In this work the decision making process for bearing selection is characterized ranging from coarse to fine criteria and addressing multiple requirements. In this way, we demonstrate an approach to balance early concept design criteria with engineering design criteria. The work presented here focuses on the engineering design process of defining rotational joints. We focus on the challenge to translate an early kinetic concept into a specification for fabrication. This process carefully integrates quantitative and qualitative criteria, i.e., a new product with a specific radial load capacity that conveys a sense of ‘sturdy elegance’. Specialists tend to draw from a selection logic based on available data, previous implementation cases including the reasoning behind bearing selection under particular operating conditions and constraints. However, past experiences may reinforce the status quo and fail to support the embodiment of creative kinetic concepts. Moreover, when access to specialists is limited or when a novel product concept challenges the established know-how, a new type of support systems is required to maintain design intent in the transition from concepts to specification. We focus on bearings since they are widely used in kinetic consumer products and heavily influence the product semantics [4]. While physical attributes are customarily used in the selection process, our goal is to support early functional prototyping that integrates kinetic design concepts and functional requirements.

2.3 Design Space of Bearings

A bearing in a rotational joint is a part that connects structural components enabling the rotation in a single axis at a friction coefficient lower than that between the two materials. The design space includes: (a) plain bearings including sleeve bearings or bushings, dry rubbing bearings and semi-lubricated bearings; (b) fluid bearings or non-contact bearings including hydrodynamic and hydrostatic bearings; (c) rolling element bearings including spherical balls and rollers (d) thrust bearings; (e) flexure bearings; and (f) customized solutions such as air and magnetic bearings. Pressure and velocity (PV) metric is used to measure performance capability and determine the safe levels of load and rotational speed.

Customary requirements include type and direction of motion, temperature, vibration, humidity, dust, space constraints, maintenance, frequency of stop/start or change of rotating direction, start and running torque, life-span, axial and load-carrying capacity, noise levels, assembly tolerances, etc. Current selection techniques draw from such factors to provide guidelines such as “for low-speed applications and moderate loads, plain sleeve bearings with boundary lubrication provide reliable long-term service and are adequate alternative to rolling-element bearings". Such selection logic fails to account for decisions related to early concepts such as "what type of bearing produces a sturdy and elegant movement for this new product?". This lack of support complicates the integration of requirements across design areas in the earliest stage of prototyping. In addition to supporting the selection of an appropriate solution, the transfer of knowledge and expertise is of key importance in this work. The goal of the proposed system is thus to support the negotiation and learning processes by providing structured information that pertains to the integration of different types of requirements.

3 Bearing Selection Attributes

In order to efficiently test rotational joints in the early stage of functional prototyping, a broad understanding of what type of bearings are used in a range of conditions -and why- is required. Furthermore, given a set of kinetic and performance attributes, often times more than one type of bearing are applicable. Hence, it is important for designers to understand the tradeoffs and make well-informed decisions in the early stage of the prototyping process to minimize resources spent on iterations. This work seeks to support the selection process with a comprehensive view that allows designers to narrow down the range of products and study sample cases and the underlying reasoning. This way, designers can obtain focused knowledge in similar conditions and understand or challenge the standards.

3.1 Macroscopic Bearing Selection (MBS)

A focused study on the method of bearing selection was carried following an inductive research approach. The fundamental attributes are extracted through an inductive study of industry cases. Such macroscopic part selection (MBS) schema aims to narrow down the field of interest and to help define the problem according to the chosen attributes across design areas. The feasibility of MBS to be used in future KBS to search for solutions is demonstrated by applying these resulting decision trees in industry cases that are not included in the training set. A complete accuracy of the decision trees is not central to this approach since the goal of the MBS is to narrow down the product range for the prototyping stage, not to suggest a single final bearing type implementation.

Several dozen kinetic product design cases were collected from commercial catalogues, case studies, and academic and industry publications. The bearing types and the reasons for their selections were recorded. Then it was checked if these products existed with other types of bearings. If multiple types of bearings are used for the same product, the reason for selection ambiguity is investigated. In most cases, clear advantages and disadvantages exist for each bearing type. Consequently, extensive arguments written by the firms and the users about the strength of each product were studied and recorded. One example of such products are CPU fans, with continuous developments in both sleeve and ball bearing assemblies. A total of 54 cases are used to build the MBS, with the aim to maximize diversity of scales, speed, load and types of motion. The collection includes: vehicle wheels from RC toys, bicycles, trains and airplanes; fans of different sizes; crane pulley; door hinge; conveyor belt rollers; castor wheel; etc.

3.1.1 Attribute Selection: Functional and Kansei Requirements

Twelve engineering attributes were initially extracted from the literature for the MBS with the product dataset. These factors were further simplified in order to support early prototyping where not all details are known, and to facilitate design exploration. The more macroscopic the factors and simpler the categorization, the easier it is for the designers to utilize such tools earlier before having to develop a detailed understanding of the products' operation environments and states. The focused selection criteria and their value ranges are: (E1) Radial Load classified in: Light, Medium and Heavy; (E2) High Speed as True and False, with a border value of 200 RPM, distinguishing joints driven by motors or engines, and those actuated by hydraulics and human force; (E3) Oscillation as True or False to distinguish between oscillating and full rotation joints; (E4) Frequent Shock Load as True and False; (E5) Long Loaded Idle Time as True or False. True, if the joint is exposed to long inoperative status and False if the joint is regularly operated; (E6) High Contamination Environment as True or False; and (E7) Geometrical Constraints as True or False. True, if the joint has a geometrical constraint and False if minimizing the bearing size may provide a significant advantage. Attributes E1, E2 and E3 are numerically definable with clear cutoff values, whilst for the rest it is less trivial to set a cutoff value.

Five kansei attributes were taken from the literature to represent the qualitative requirements that describe the character of movement in kinetic products [11]. These attributes are defined as antonym pairs as is customarily in Semantic Differential (SD) evaluations: (K1) Dull-Exciting; (K2) Clumsy-Graceful; (K3) Unrefined-Elegant; (K4) Playful-Serious; and (K5) Delicate-Sturdy. The extraction of kansei values depends on the design goals defined by the team [11]. Special emphasis was put in evaluating the type of movement, rather than the overall product; namely, SD evaluations can contrast the artefacts "bicycles" versus "motorcycles", or a generic type, such as mountain bicycles vs. foldable bicycles, or a set of competing brands or models. Here the type of movement enacted by a rotational joint is evaluated, i.e., the semantic profile produced by bicycle handle brake levers is compared to the type of movement produced by bicycle pedals (Fig. 1).

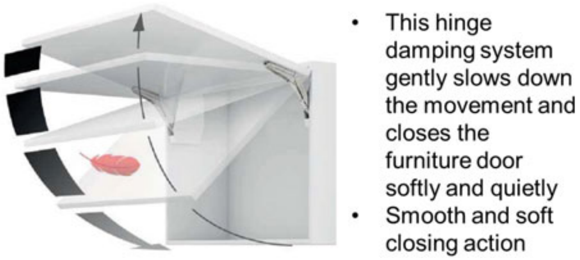

Fig. 1 The 2014 hinge catalogue by Hafele™ refers to attributes ‘smooth’, ‘soft’, ‘gentle’

3.1.2 Attribute Filtering and Assessment

The sets of engineering attributes were tested for their level of significance in influencing the bearing selection process. This preliminary analysis aimed to test the feasibility of building decision tree models and to screen out the non-significant attributes before validating the data with a panel of raters. The variables were first filled out by the authors and pre-tested using *RandomTree* classifier in WEKA [12]. For the engineering factors, the *RandomTree* analysis yielded only three mismatches—such 0.94 accuracy shows the feasibility of the engineering selection decision tree model and suggests that these attributes are good predictors of the bearing type selection. As the next step, the *SelectAttribute* function with *InfoGain* classifier and *Ranker* method in WEKA was used in order to narrow down the attributes to a few that had the most significant impact and still give a relatively accurate decision tree [12]. The most significant variables were identified as: (E1) Radial Load, (E2) High Speed, (E3) Oscillation, and (E4) Frequent Shock Load. These four engineering attributes were used for the assessment by raters. All five kansei attributes were used in the assessment with no preliminary filtering.

Seven design engineers were consulted for an inter-rater reliability study. These included three professors and four students enrolled in the MIT-SUTD engineering graduate program. The survey was conducted in two sets, each containing 27 products out of 54 and columns: Radial Load, High Speed, Oscillation, Frequent Shock Load and Level of Confidence. Each cell was rated from 1 to 6, 1 being ‘Strongly Disagree’ and 6 being ‘Strongly Agree’. This scale was designed to avoid neutral values and to allow for the conversion of the numerical average into a binary of True and False, where average values between 4 and 6 were converted to True and values between 1 and 3 were converted to False. The column Level of Confidence represented the rater’s degree of understanding of the particular product. Radial Load Class was not included in the survey as the weight ranges for each product is extracted from the literature.

Four product designers were consulted for the rating of the kansei attributes. The raters have more than 10 years of experience in product design. The kansei survey was conducted in a single set, with all raters evaluating the full product dataset applying the five attributes. The scoring system for this assessment ranged from 1 to 5, representing the corresponding term in the SD pairs, i.e., 1 for “Very Dull”, 2 for

"Somewhat Dull", 3 for "Not applicable", 4 for "Somewhat Exciting" and 5 for "Very Exciting" in attribute K1. Neutral values are allowed since some kansei attributes may not be clearly applicable to certain products, either because the semantic character of the product dominates the characterization of its movement, or because the joint is usually blocked from view.

For both evaluations, the collected surveys were subjected to percentage overall agreement and the values for each column were calculated. Cohen's Kappa was included as a more robust measurement of the degree of agreement. The confidence level of the survey participants were used to spot items with exceptionally high disagreements or low average confidence level and to remove those outliers from the reliability and the rest of the decision tree study.

4 Decision Trees

The decision trees were built with WEKA using *RandomTree* classifier in the same manner as the preliminary analysis previously described. As an initial step, by using only the four most critical engineering attributes and the five kansei attributes, the system remains simple and becomes easily approachable to designers from different areas. The resultant decision trees and the pattern outliers were investigated as to why such combination of attributes prompted utilization of certain types of bearing and what unique conditions cause some products to fall outside the pattern, if any. Once the decision trees were built, the branches containing outliers were identified and the reasons for the discrepancies discussed. The trees were then updated by merging multiple branches or further developing branches in order to improve the accuracy of the rule base. In this paper, the focus is on the distinction between plain and rolling element bearings due to availability of information and sample products–future studies will analyze complementary criteria of scale, load and speed.

4.1 Engineering Criteria

Figure 2 shows the decision tree when considering the engineering requirements of a kinetic design using bearings. "Oscillation" has the largest effect as plain bearings dominate the area of oscillating joints—17 out of 20 cases. Examples include door hinges, radial dam gate trunnion bearing, rudder bearing in marine vessels, various construction machine joints and engine rocker arm bearing. However as the radial load, the rotating speed and the rotating angle increases, some transitions into other bearing types are registered.

As "Radial Load" increases, it presents a general shifting pattern from mostly plain bearing to mostly rolling element bearing utilization–except for lightweight products with very high RPM. This is due to the higher friction coefficient of the plain bearings that begin to substantially increase the force required to rotate, wear of the bearing and heat generation even at low speed with the significantly larger

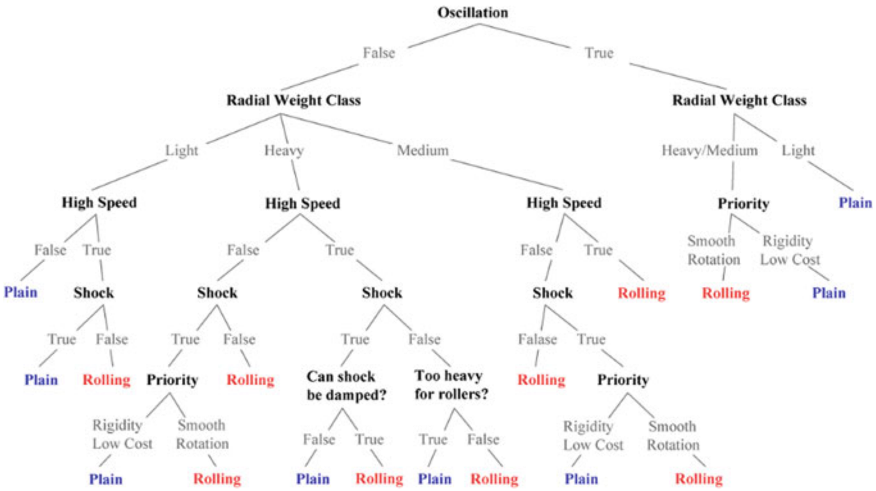

Fig. 2 Decision tree applying engineering attributes to the selection of bearing types

normal forces. "High Rotational Speed" is directly proportional to wear volume. Higher wear constants and lower hardness values of typical plain bearing materials naturally do not suit high RPM environments unless full hydrodynamic fluid film can be generated. Twelve out of 15 high speed full rotation cases have rolling element bearings. Examples of these products are ceiling fan, machine tools, induction motors and transmission shaft and gear bearings.

Lastly, higher "Frequent Shock Loads" can lead to quick premature failure of rolling element bearings. This attribute alone did not impact the bearing selection to a significant degree. Amongst all joints determined as frequent shock load exposed (32), fourteen are equipped with rolling element bearings while eighteen use plain bearings. Nevertheless, this attribute impacts the selection process when paired up with attributes such as low rotational speed or oscillatory movement. Five out of seven low speed, full rotational and frequently shock loaded joints were plain bearings while nine out of eleven oscillating and frequently shock loaded joints were plain bearings. Some examples include large construction equipment, swing bridge wheels and bike pedals. Under these circumstances, the lower rotational friction seems to be sacrificed for rigidity, durability and reliability just like in the case of radial dam trunnions.

4.2 Kansei Criteria

Figure 3 shows the decision tree considering the kansei requirements of a kinetic design using bearings. The kansei variables determined by the affinity clustering are termed K1–K4. Attribute K3 has the largest effect, with "Elegant" as the

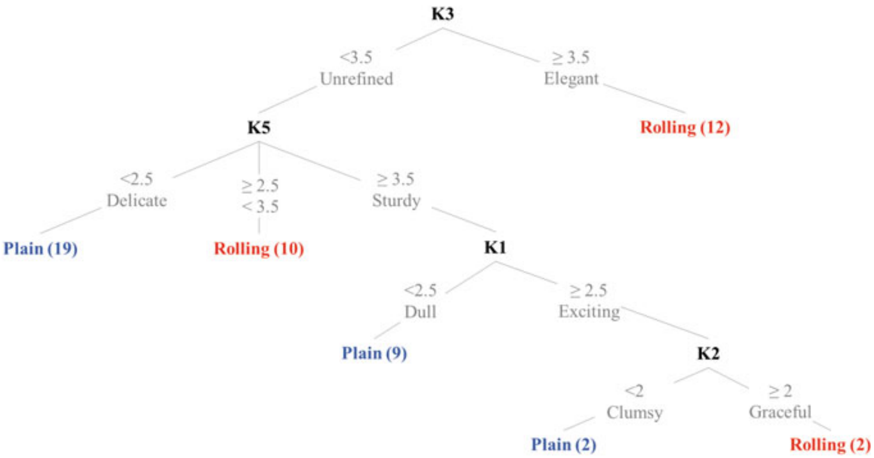

Fig. 3 Decision tree applying kansei attributes to the selection of bearing types

distinguishing factor for half of the 24 products using rolling element bearings. The set of products ascribed an elegant motion includes ceiling fan, Ferris wheel, paper mill roller, and train wheel axle.

Attribute K5 identifies three groups: products registered as having a "Delicate" movement separate 19 cases that use plain bearings, an intermediate group for which the raters agreed on neutral values for 10 rolling element bearings, and the remaining "Sturdy" products, all of which have plain bearings except for two products evaluated with high K1 and K2 values ("Exciting" and "Graceful"), which use rolling bearings. The two products with rolling bearings that combine such characteristics (Unrefined-Sturdy-Exciting-Graceful) are: wind turbine rotor and aircraft landing wheels. In comparison, the two products with plain bearings that differ only in the last attribute (Unrefined-Sturdy-Exciting-Clumsy) are: dump truck hydraulics joint and construction machine track chain.

Noticeably, attribute K4 ("Playful-Serious") does not have a significant impact, which is confirmed by this being the only attribute with a mode value = 3 (neutral) in the assessment by raters.

4.3 Decision Tree Testing

Beyond the engineering and kansei attributes considered here, other type of factors play a significant role in bearing selection, including market preference, availability, quality and cost trade-offs. In many cases, multiple bearing types may satisfy the requirements with not too significant cost, functionality and kansei differences. To help designers identify the trade-offs, the decision trees presented here are intended to support the transition from conceptual to engineering design. To validate this, a recent industry case led by the authors is presented. The kinetic design *WaveGarden* initiated as a request to conceive, design and implement an interactive exhibition to embody principles of energy efficiency. The brief included requirements such as low maintenance, low power consumption, located outdoors in a tropical climate, and attractive appearance, among others. A space of 4 × 4 m was allocated. The conceptual design stage was led by a professional designer and supported by a group of first year undergraduate design students. The resulting design concept consisted of a modified version of a device demonstrated by J. Shive in his 1959 educational film "Similarities in Wave Behavior" [13]. The Shive wave machine sits on a tabletop and consists of an array of a few dozen small steel rods welded to a thin axle torsion bar that is perpendicular to the aligned rods. The torsion wire transmits energy from one rod to the next, while the high moment of inertia demonstrates wave transmission by ensuring the wave takes several seconds to traverse the entire series of rods. The design team chose the agile and smooth motion of the Shive wave machine as the main inspiration for *WaveGarden*. The concept was presented to the client as a four-meter long exhibition that could be actuated directly by hand with a gentle movement of the first rod. The client approved this design concept based on the appealing movement that would promote contemplation and trigger curiosity about the underlying science when displayed in a public area.

An example rendering of *WaveGarden* is shown in Fig. 4. The main challenge in the embodiment of *WaveGarden* was to achieve a trade-off between several parameters at the scale proposed for this kinetic design. A total of 60 thin-walled stainless steel pipes 1500 mm long were to rotate about the spine, and bearing selection became a critical step where engineering and kansei requirements needed to be balanced. It was decided that the pipes were to transmit the movement by

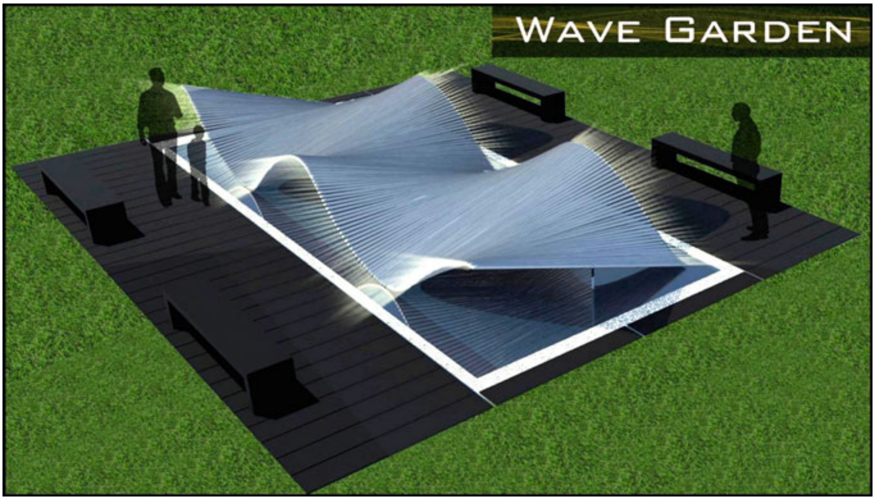

Fig. 4 Kinetic design project "WaveGarden"

connecting them with an elastic rope so that the rope tension could be used to calibrate the desired movement. A type of bearing was needed that would provide the minimum possible friction at this scale, as fluent movement gave this exhibition its unique character.

Based on the engineering decision tree, the decision to build initial prototypes was narrowed down to the use of plain bearings since the pipes oscillated and were less than 3 kg each (Fig. 2: "Oscillation" and "True and Radial Weight" Light). This type of decision aids save time and effort to narrow down the design choices and to avoid wasteful consideration and experimentation with other bearings, for example by assuming in this case that ball bearings would have a lower coefficient of friction. If ball bearings were used to prototype this design, the lubricant in the bearings would need to be removed in order to achieve a similar smooth rotation as plain ABS plastic sleeves due to the thickness of the grease, which of course would not be an appropriate solution for an outdoor exhibition.

In respect to the kansei decision tree, two values were selected to capture the intended type of motion of *WaveGarden*: Delicate and Graceful. Most low K5 values (Delicate) in Fig. 3 do point to plain bearings with a total of 14 of them also having high K2 values (Graceful). The norm in this subset is the use of plain bearings such as in trash bin rotating swing lid and windscreen wipers. The exceptions are products with high K3 values (Elegant) such as optical disk drive spindle which use rolling element bearings. In sum, *WaveGarden* fits well in the subset of "Oscillation" True, "True and Radial Weight" Light, low K5, and high K2. Other products with a light load, oscillate and denote delicate and graceful motion include: small walking robot leg joint, trash bin swing lid, and windscreen wiper joints. One key design consideration that could be misleading in the bearing selection process for *WaveGarden* is its atypical envelop size, as it is significantly larger than the size of the products in this category. However, the decision trees successfully narrow down the search and make the process manageable while maintaining the early design intent. This result was validated in the early prototyping phase. An early prototype was fabricated using roller bearings, and while it was known this selection would not be ideal for engineering reliability, it was surprising the compromise it made on the kinetic aesthetic. Dynamic misalignments were more obvious and the motion stalled out too quickly. Later prototypes with the plain bearing selection eliminated these issues and made for an improved dynamic motion.

5 Discussion

This paper offers a systematic approach to support design teams integrate quantitative and qualitative specifications maintaining early intent in the design and development of innovative kinetic products. Whilst maintaining design intent is important to ensure quality, support creativity and execute product strategy, it is often compromised in a chain of decisions, leading to innovativeness and implementation shortcomings. The approach is validated by applying the decision trees to a real industry case and demonstrating its supporting role to shortlist a manageable set of options for embodiment of kinetic designs. Future work will refine and complement the product datasets with other components, and will study the application of this macroscopic view in two complementary modes: "Maintain Intent" and "Derive Intent". The former consists of applying this approach once a conceptual design has been produced—as demonstrated in this paper. The latter consists of using this approach in creative ideation as an inspiration to imagine innovative kinetic design concepts based on juxtaposing sets of seemingly unrelated products to extract non-obvious applications of rotational joints.

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