INTERNATIONAL CONFERENCE ON ENGINEERING DESIGN, ICED11
15 - 18 AUGUST 2011, TECHNICAL UNIVERSITY OF DENMARK

MODELS AND SOFTWARE FOR CORRUGATED BOARD AND BOX DESIGN

Vahid Sohrabpour[1] and Daniel Hellström[2]
(1) Lund University, Sweden (2) Lund University, Sweden

ABSTRACT
To design and develop boxes which protect, and at the same time utilize fiber material efficiently, models and software for predicting corrugated board and box properties are needed. The purpose of this research is to provide propositions toward improving the use and development of models and software for corrugated board and box design. By using an abductive approach, 18 models and four software for predicting corrugated board and box properties were identified, compared, and categorized depending on the needs of different supply chain actors. Eight of the models use paper properties for predicting board properties while ten models predict corrugated box properties. In order to decrease the gap between theory and practice new insights, in the form of propositions toward improving the use and development of models and software for corrugated box design, are suggested. A holistic perspective for modeling corrugated board and box is proposed and enables practitioners and researchers to identify causes to variation in predictions by considering control and noise factors.

Keywords: Prediction model, simulation, packaging design, corrugated, board, box

1 INTRODUCTION
Corrugated boxes have been used for protecting products for over a century. To design and develop boxes which protect, and at the same time utilize fiber material efficiently, models and software for predicting corrugated board and box properties are needed. Without these predictive models and software the corrugated industry needs to produce a set of samples and conduct physical tests which involve high costs and require more time.

There are reports available since the 1940s which show that researchers have been attempting to predict the behavior of corrugated board and box (e.g. [1]).Moreover, as [2] express, “Researchers have attempted to generate predictive equations that would reliably estimate box compression strength without requiring the actual production and testing of every box”. However, despite the great amount of theoretical research in the field, there is a research gap in how these models and software can contribute to the needs of industry in corrugated box design. In order to decrease the gap between theory and practice, the following research questions are addressed: *What models and software are available for predicting corrugated board and box properties? How do different supply chain actors in the corrugated industry use these models and software?* The purpose of this explorative research is thus to provide propositions toward improving the use and development of models and software for corrugated board and box design in industry practice. In order to do this, models and software for predicting corrugated board properties are identified, compared, and categorized depending on the needs of different supply chain actors.

The focus of this research is on models and software which are used on paper, board or box levels. Modeling of corrugated board can be performed on different levels and to various degrees of complexity, see Figure 1. This starts from the most detailed level on a molecular length scale and continues to micro fibrils, fiber, paper, board, and box and stretches to piles of boxes (on pallet and/or in truck). These models make use of various measured parameters at each level and predict performance at the next level.

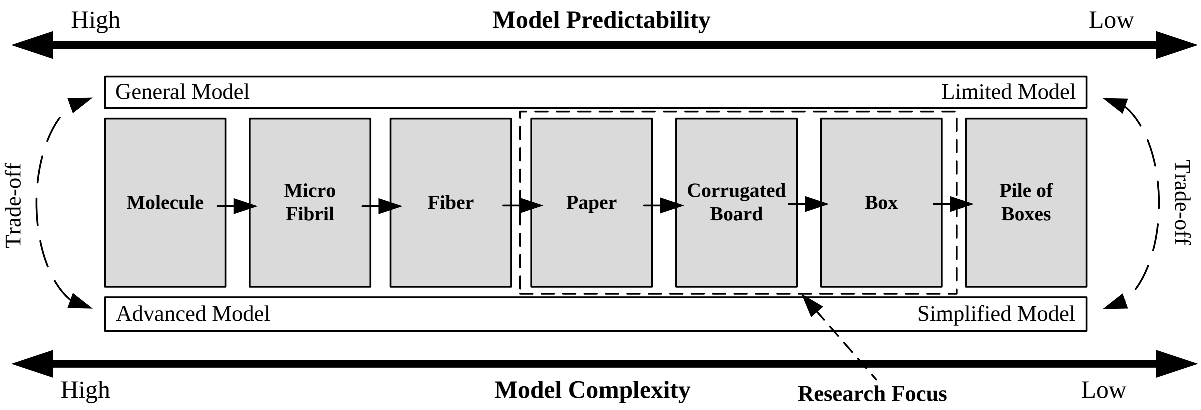

Figure 1. Research focus and the trade-offs between complexity and predictability

2 METHODOLOGY

This abductive research started with corrugated board and box modeling review, and experience from previous empirical data in the field, and then the research purpose was set. The abductive approach has been used in various disciplines such as neural networks, logic, learning, artificial intelligence, and computer science. The aim of using this approach for this investigation is to understand the phenomenon (predicting corrugated board properties), as [3] point out, in order to suggest a new theory in the form of propositions [4] for use of models and software in practice.

As demonstrated in Figure 2, literature searches and interviews with experts were the data collection steps used in order to identify existing models and software. To gain knowledge about the corrugated industry, internal company reports were reviewed at Tetra Pak. These reports dealt with the manufacture of corrugated board and box in different countries. In parallel, group discussions with experts and field visits were conducted to find out how industry currently uses models and software to predict the properties of corrugated board and boxes. The analysis was carried out continuously in the data collection process where various gaps and challenges were found in theory and practice. Finally, the results and discussions were reviewed by industry representatives in order to strengthen the propositions.

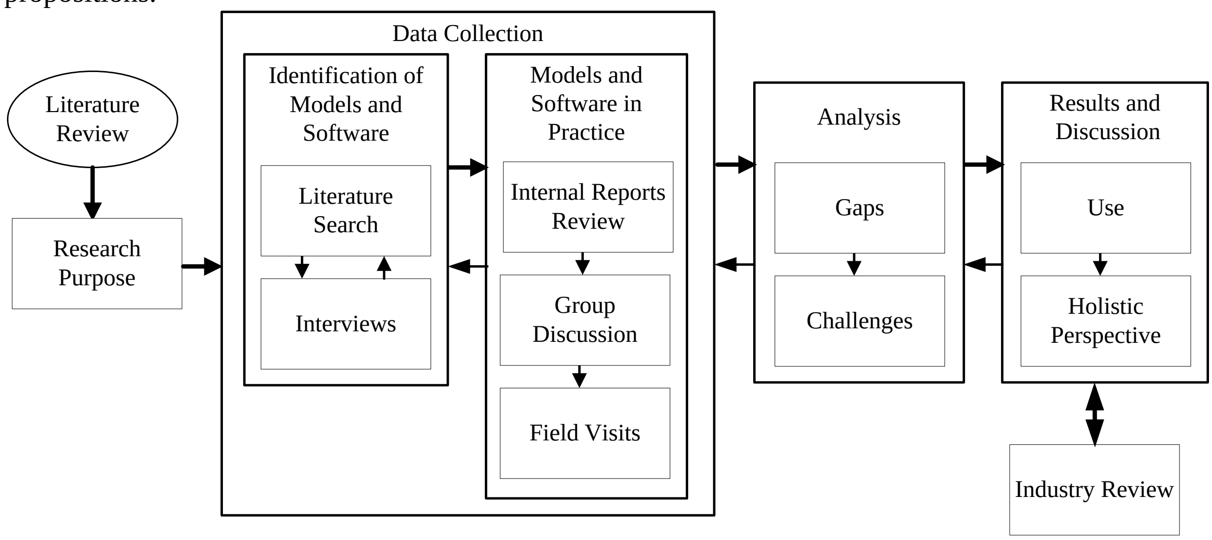

Figure 2. A schematic illustration of the research process

3 MODELS AND SOFTWARE FOR CORRUGATED BOX DESIGN

18 models and four software programs for corrugated box design were identified in this investigation. These have been developed based on a numerical or an analytical/empirical approach. The analytical/empirical approach is based on physical tests and analysis while the numerical approach is based on finite element method (FEM). The majority of the models and software have been developed based on an analytical/empirical approach, but the last decades of advancement in computer capacity have enabled FEM to be used. A timeline is used in Figure 3 to illustrate the progress of the models

and software identified. One identified piece of software, namely the SCA software, is not explained in detail in this investigation because access to the software was restricted by company (SCA).

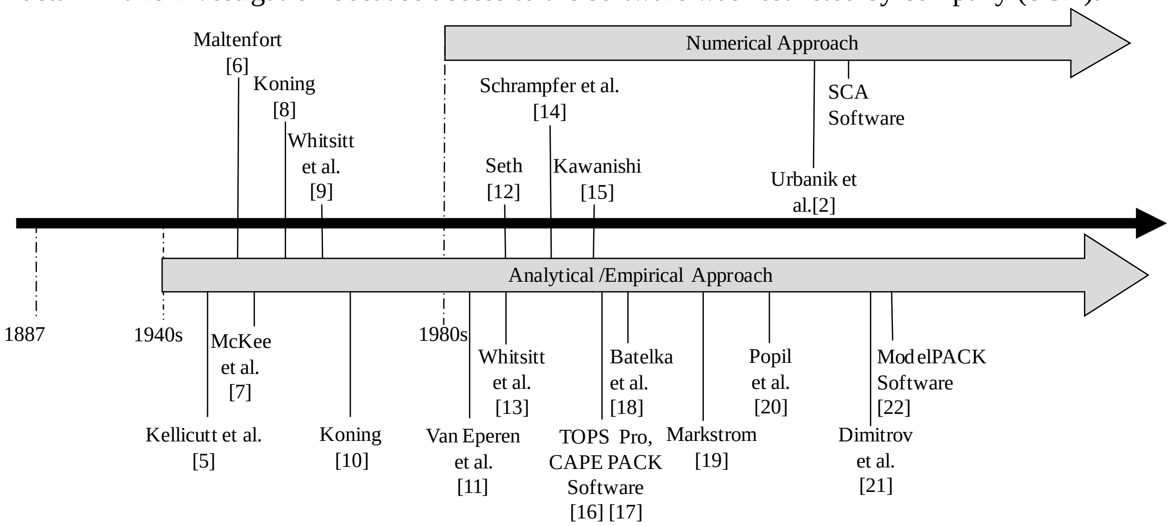

Figure 3. Progress of models and software identified

The scope of the models and software identified ranges from paper level to board level and to box level. Figure 4 provides an overview of models and software and the different related levels. The main input and output properties used in different models for paper, board, and box levels are the following: Ring Crush Test (RCT), Short Span Compression Test (SCT), Concora Liner Test (CLT), Edge Crush Test (ECT), Flexural Stiffness in Machine Direction and Cross-machine Direction (MD, CD), Box Compression Test (BCT), and Stacking Strength (SS). Depending on the scope of a model, it uses some of these parameters to provide a mathematical prediction of the others. The relationship between these properties at different levels and related parameters is as follows: Paper (RCT or SCT) → Board (ECT) → Box (Short-term strength/BCT) → Box (Long-term strength/Stacking Strength). Among these parameters, stacking strength is one of the most useful box parameters which can be estimated based on the BCT. In contrast to the BCT which is conducted in ideal conditions in the laboratory, stacking strength considers environmental factors, e.g. for stacking time and humidity (Adapted from [23]).

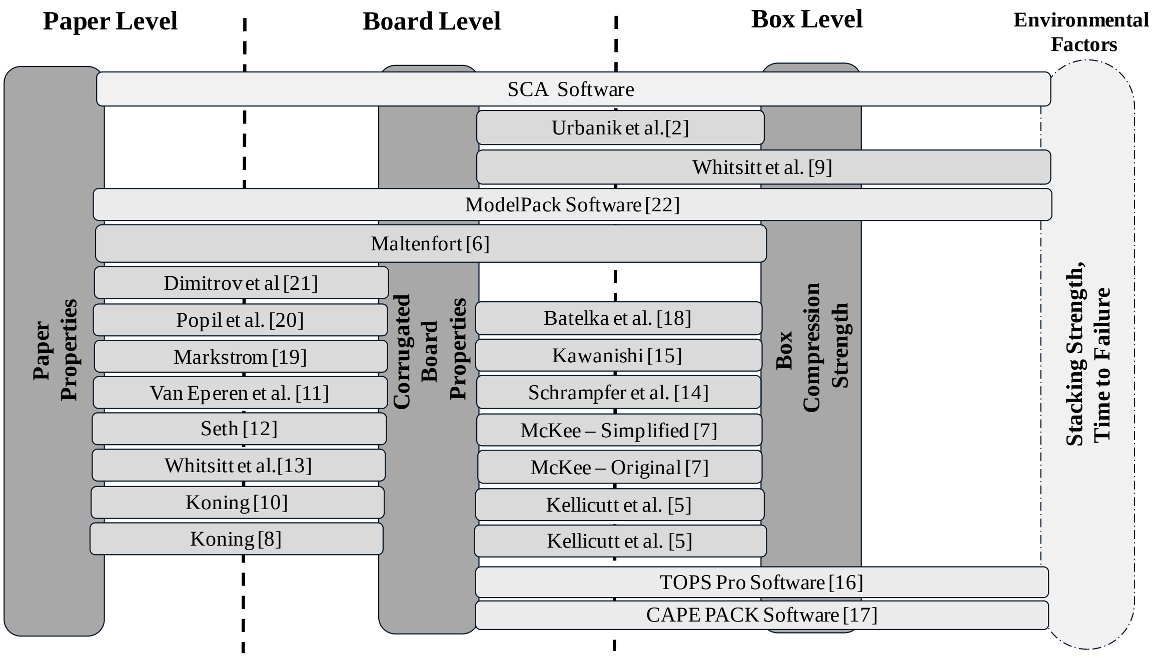

Figure 4. Scope of models and software identified

Eight identified models use paper properties for predicting board properties. These models use RCT or CCT or SCT as main paper properties for predicting ECT. The only model which takes the corrugating impact into consideration is Seth's model [12] which is an exception to all the models identified. Table

1 presents details about each model for input, output, and assigned test method, and knowledge needed for use.

Table 1. Models for predicting corrugated board properties

				Koning [8]	Koning [10]	Whitsitt et al. [13]	Seth [12]	Van Eperen et al. [11]	Markström [19]	Popil et al. [20]	Dimitrov et al. [21]
Input	Paper	RCT (CD)	Liners	X				X	X		X
			Medium	X				X	X		
		CCT (CD)	Liners						X		
			Medium						X		
		SCT (CD)	Liner			X	X		X	X	
			Medium			X	X		X	X	
		Constant	Flute				X				X
			Corrugating Plant				X				
		Measurement Constant (RCT vs. CCT vs. SCT)							X		
		Facing Thickness			X						
		Fluting Takeup Factor		X	X	X		X	X	X	
		Empirical Constant								X	
	Board	Flexural Stiffness	MD							X	
			CD							X	
		Corrugating Medium Thickness			X						
		Flute Spacing			X					X	
		Buckling Coefficient			X						
		Modulus Elasticity (CD)			X						
Output	Board	ECT		X	X	X	X	X	X	X	X
Assigned Test Method			TAPPI				X	X			
			FEFCO						X		
Knowledge Needed for Use			Structural Mechanics	X	X	X	X	X	X	X	X
			Fiber Mechanics	X	X	X	X	X	X	X	X

Ten models which predict corrugated box properties are identified in this investigation. Eight of these models use corrugated board properties to predict box compression strength. Maltenfort model [6] uses paper properties to predict box compression strength. Whitsitt et al. model [9] use paper to predict Time to Failure for corrugated boxes. Among these models Kellicutt et al. model 2 [5] propose a relation between moisture content and compression strength of corrugated boxes [24]. Kawanishi model [15] is the only one which takes the impact of print and moisture content on box compression strength into account. The details regarding each model for input, output, container type, assigned equipment, test method, and knowledge needed for use are presented in Table 2.

[7] provides the most influential model for predicting box compression strength. However, according to [18], the limits of the McKee model [7] is that it "only applied to regular slotted container (RSC), to boxes where the length was less than three times the width and boxes where perimeter was less than seven times the depth." Different versions of this model are available and it has been the basis for many researchers in the field, e.g. for [9], [18], and [2]. These researchers have further developed the McKee model by adding new factors or expanding predictions beyond its limitations. [14] has, for example, adapted the McKee model to different cutting methods and equipments, which resulted in four variations based on TAPPI, SCAN/Billerud, Weyerhaeuser, JTF/Billerud cutting methods and equipment.

The simplified McKee model [7] is less accurate compared to the original McKee model but it is easier to use. According to interview respondents most industry experts are using it and have done so for a long time. The main difference between this model and the original one is that flexural stiffness (MD, CD) is substituted by board thickness. Consequently, constants in the model are also revised.

Batelka et al. model [18] includes "Bliss case and die cut boxes" in addition to RSC, and expands the applicability to all aspect ratios of length to width. It also includes a specific package depth term in the equation. Their research emphasizes the importance of the impact of box plant quality issues such as flap scoring, slotting depth, fishtailing, and localized crushing on scaling constants in the model. Therefore, they propose that every company needs to verify the equation with its own packages.

The Urbanik et al. model [2] is based on the results of FEM and they claim that it gives physical meaning “to what were previously only fitting parameters and it can serve as a tool for additional explorations in box optimization”. Furthermore, they claim that “This work is necessary if the corrugated box industry hopes to understand its product well and achieve materials savings and economy by reducing product variation”.

Table 2. Models for predicting box properties

				Kellicutt et al. 1 [5]	Kellicutt et al. 2 [5]	Maltenfort [6]	Original McKee [7]	Simplified McKee [7]	Schrampfer et al. [14]	Whitsitt et al. [9]	Kawanishi [15]	Batelka et al. [18]	Urbanik et al. [2]
Input	Paper	RCT (CD)	Liners	X									
			Medium	X									
		CLT (CD)				X							
		Flute Constant		X									
		Liner Type				X					X		
		Weight Liner									X		
		Weight Fluting									X		
		Corrugation Ratio									X		
	Board	ECT					X	X	X	X	X	X	X
		Moisture Content			X						X		
		Flexural Stiffness	MD				X		X	X			X
			CD				X		X	X		X	X
		Empirical Constant			X	X							
		Thickness						X			X		
	Box	Perimeter		X			X	X	X	X	X	X	
		Applied Load Ratio								X			
		Stacking Time								X			
		Box Constant		X									
		Width of Panel				X						X	
		Depth				X						X	X
		Length				X							X
		Poisson’s Modulus											X
		Printed Ratio									X		
		Buckling Ratio								X			
Output	Box	Compression Strength		X		X	X	X	X		X	X	X
		Stacking Strength			X								
		Time to Failure								X			
Container type		RSC				X	X	X	X		X	X	X
		WA									X	X	
		Bliss Case										X	
		Tube		X	X								
Assigned Equipment and Test Method		TAPPI							X				
		SCAN/Billerud							X				
		Weyerhaeuser							X				
		JTF/Billerud							X				
Knowledge Needed for Use		Structural Mechanics		X	X	X	X	X	X	X	X	X	X
		Fiber Mechanics		X					X	X			X

Four software programs which predict stacking strength are identified in this research. CAPE PACK and TOPS Pro use board properties and environmental factors as input, and ModelPACK uses paper properties to predict stacking strength. Details about CAPE PACK, TOPS Pro, and ModelPACK for input, output, box type, and knowledge needed for use are shown in Table 3.

The only FEM-based software identified in this research is from SCA. According to SCA, this software has been developed over 20 years and considers creep and humidity in its predictions. This software visualizes stress points and deformations, and provides higher accuracy compared to empirical models. FEM has been introduced to predict the behavior of corrugated board and box in industry to achieve higher accuracy and provide more details in corrugated board and box behavior. These simulations use paper properties to provide insights into the behavior of the box. These simulations can also use box properties and provide insights into the behavior of the box using different environmental factors. Providing regression models from this software can increase accuracy compared to the empirical models available, and provides more user-friendly software for packaging- and logistics engineers.

Table 3. Software for predicting stacking strength

			CAPE PACK [16]	TOPS Pro [17]	Model PACK [22]
Input	Paper	Thickness			X
		Basis Weight			X
		CCT			X
		SCT			X
		CMT			X
		Burst			X
		Tensile Stiffness			X
		Stretch at Break			X
	Board	ECT	X	X	
		Caliper	X	X	
		Perimeter	X	X	
		Humidity	X	X	
		Storage Time	X	X	
		Case Dimension	X		
		Flute Constant		X	
		Shape Factor		X	
		Length-to-Width Ratio Factor	X	X	
		Direction of Fluting	X	X	
	Box	Case Types	X		
		BCT		X	
	Environmental Factors	Pallet Surface Factor	X	X	
		Overhang	X	X	
		Internal Support	X	X	
		Printing	X	X	
		Divider Type	X		
		Flap Gap Factor		X	
		Interlock	X	X	
		Creep			X
Output	Board	Thickness			X
		Basis Weight			X
		Bending Stiffness			X
		ECT			X
		FCT			X
		Bursting Strength			X
	Box	Stacking Strength	X	X	X
Knowledge Needed for Use	Packaging Engineering		X	X	X
	Logistics Engineering		X	X	
	Structural and Fiber Mechanics				X
Models Used		Simplified McKee [7]	X	X	X
		Kellicutt et al. 1 [5]		X	
		Urbanik et al. [2]			
Board Type		Single Wall	X	X	X
		Double Wall	X	X	X

5 DISCUSSION AND PROPOSITIONS

In Figure 6 the applicability of different models and software is illustrated and compared. The comparisons consider characteristics of each model depending on whether they use paper, board or box properties, and on whether they include environmental factors.

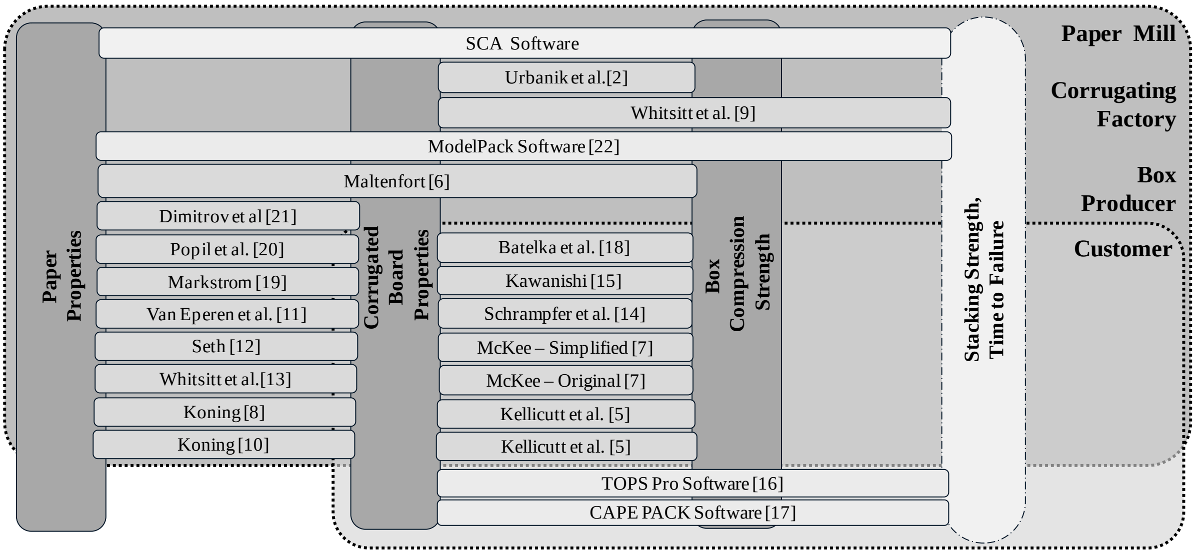

Figure 6. Applicability of models and software for different actors in packaging industry

5.1 Supply Chain Use of Models and Software for Corrugated Box Design

Our investigation shows that the models and software which use paper properties to predict box compression strength or stacking strength are applicable for packaging industries such as paper mills, corrugation factories, and board and box producers. This applicability is mainly because of the access of these industries to paper properties which may enable more accurate prediction of box properties in their design and selection of corrugated boxes. On the other hand, the focus in these types of models is to achieve efficiency in production by utilizing material. Our investigation also shows that these models and software always need revision, based on tests in each corrugating factory and box producer, to adjust the regression formulas to the impact of production processes. Although box producers are capable of using paper or board properties, they still use models which consider paper properties in order to make more accurate predictions of board or box properties. These types of models are used mostly by physicists and fiber mechanics experts.

In contrast, only models which use board properties are applicable for customers (buyers) of corrugated boxes, since they do not have access to paper properties; however, they can measure board properties. These types of software (e.g. CAPE PACK and Tops Pro) are useful as they choose the most effective package for the intended logistics and climate conditions rather than just increase the maximum efficiency in material production. Lack of knowledge about paper and the inability to measure paper properties represent a major barrier for customers of corrugated boxes if they are to use models which can predict box properties based on paper properties. Software available to customers appeals more to packaging designers/engineers and logistics engineers by including more environmental factors from the logistics and distribution of the filled boxes. Nevertheless, there is no model covering the entire scope from paper properties to environmental factors which consider the impact of the distribution process for the final consumer/customer (e.g, logistics, handling, load frequency, cyclic humidity, etc.). Consequently, the following propositions are made:

Proposition 1**:** *Knowledge, information- and data sharing regarding corrugated board and boxes between different actors in the supply chain from paper mill down to customer is needed in order to improve prediction accuracy. This would enable effectiveness and efficiency of the box design by considering material and process uniqueness, such as production processes and material composition.*

Proposition 2**:** *There is a potential business case for companies which have a massive amount of knowledge and advanced software for simulating corrugated board by selling knowledge or renting out their software. Such a win-win situation helps customers or producers of corrugated board to optimize their package designs while companies owning models and software can rationalize the cost of developing models and software.*

5.2 Toward a Holistic Perspective

One major problem encountered in this investigation was the lack of holistic perspective in developing models and software for prediction of corrugated board and box properties. There are many factors which decrease the accuracy of predicting corrugated board properties. In this section, this main

challenge in modeling of corrugated board and box is addressed, and some effective ways to exploit its capabilities available are proposed.
The use of the P-diagram ([25] and [26]) from robust design methodology provides a holistic modeling perspective for corrugated board and box which provides an opportunity to identify variations in predictions by including various noise factors. [2] reveal that “However, the difference between experimental variability and modeling variability is a real cost associated with box production, resulting in boxes that may be over-designed to compensate for a lack of model precision. Improving the accuracy of our models would remove some of this extra cost from the manufacturing process.” Since prediction of corrugated board and box properties involves various noises, robust design methodology is used in Figure 7 to visualize a potential holistic perspective.

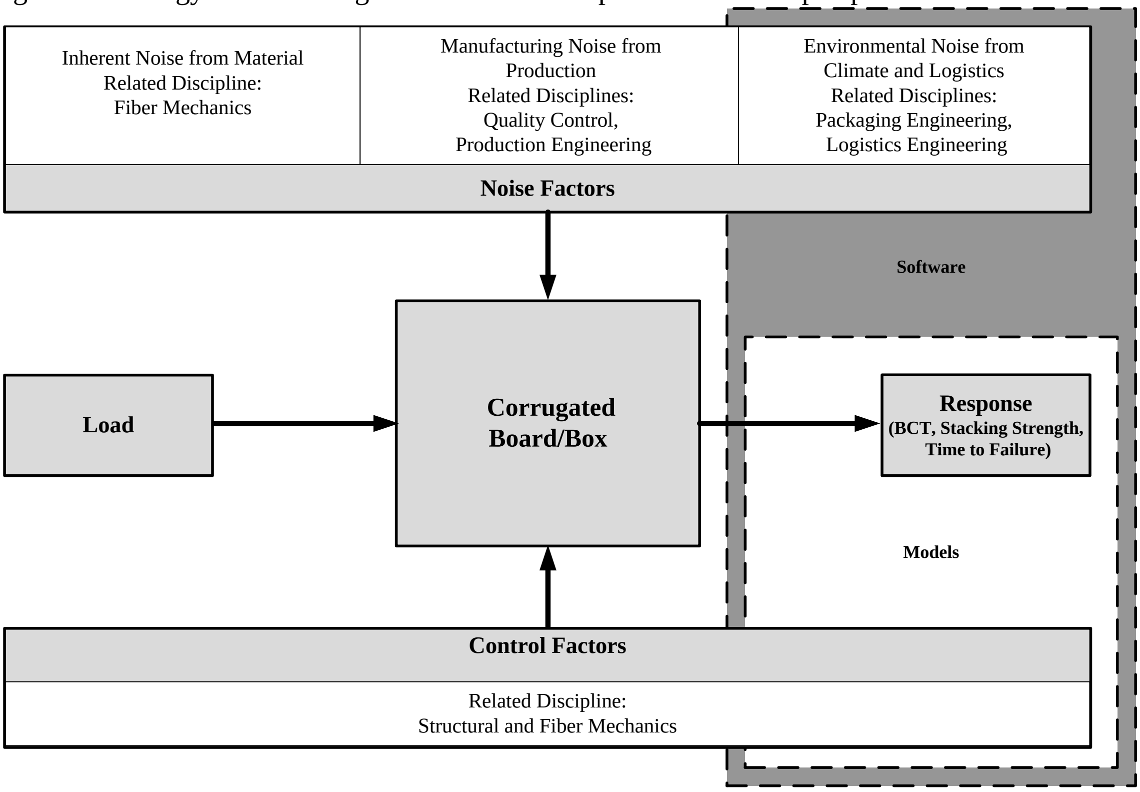

Figure 7. Holistic perspective for modeling corrugated board and box

Inspired by a P-diagram and viewing the box as a system, there are two factors influencing the response of the box i.e. noise and control factors. These factors are fundamental in increasing the quality of boxes from both production and use perspectives, and for increasing the prediction quality. Control factors are those which physicists and packaging scientists in the paper physics discipline use in the absence of most noise factors in order to predict response of the box in some type of performance (e.g. BCT, stacking strength or time to failure).
Noise factors occur along the supply chain of corrugated boxes, and supply chain, logistics, and quality engineering are disciplines which consider them. Considering these noise factors in models and software is vital to ensuring practical, more accurate prediction.
There are three types of noise factors: Manufacturing, Environmental and Inherent noise. Manufacturing noise in production has a significant impact on the ECT and BCT of corrugated board and the box ([18] and [27]). Manufacturing noise is mainly reported in research on board and box producers but also exists in the paper mill and the corrugating factory. Consequently, there is a need to use factory-made packages for developing models rather than the ones made in the lab using a cutting table if manufacturing noise is to be measured. Seth’s model [12] assigns a constant for the corrugating plant and fluting to address this type of noise in predicting ECT. [18] point out the importance of the impact of box plant quality issues such as flap scoring, slotting depth, fishtailing, and localized crushing on scaling constants in the formula. The authors therefore propose that every company needs to verify the equation with its own packages. We accordingly put forward the following proposition:
Proposition 3: *To make more accurate predictions of corrugated board and box properties it is vital to measure and consider manufacturing noise in prediction models and software.*

Environmental noise factors are the ones which happen in the downstream supply chain/distribution of corrugated boxes and which are considered by packaging logistics engineers, packaging designers, logistics engineers, and quality control/claims departments at the customer's. This noise is considered mainly by software rather than theoretical models. Software uses some safety factors to roughly estimate the impact of noise factors. The third noise factor is the inherent type. This noise is considered by packaging engineers working in paper-, board-, and package production. Two examples of this type of noise are the aging of material and local variation of fiber density in the paper.

Tables 1, 2 and 3, show a major difference in the focus between models and software. Models are focused more on control factors in the absence of environmental and manufacturing noise. On the other hand, software is more focused on pragmatic estimations considering environmental noise and on providing features to change formulas for considering different noise in production of corrugated boards and boxes. The difference in the focus of models and software is also shown in Figure 7.

This holistic view of modeling corrugated board and boxes is not only useful in a traditional way to increase box quality, but also it provides the foundation for providing more accurate, more practical models and software. For example, models provided by academic research consider control factors and they are not deeply involved in all noise factors whereas software developed in industry tries to cover environmental noise factors and use academic models as its foundation. Moreover, manufacturing noise factors are the less focused-on part of software and models. Using handmade boxes to provide models ignores their impact on box performance. Variation in production quality, which is very high from each factory to another and from country to country, makes it even more difficult to provide universally applicable models and software. In addition, inherent noise factors which come from the material *per se* are another problem which paper mills are usually aware of. Variation in fiber strength and fiber-fiber bond strength are the roots of this noise and it has a drastic impact on creep tests and cyclic humidity. Predicting the stacking strength of boxes is very dependent on the amount of recycled fiber used in the paper. A great number of tests by Billerud has shown that boxes using recycled material have a drastically shorter time to failure. A description of ModelPACK, an EU project, reveals that "variability in raw materials (packaging grade papers) with increasing percentages of recycled fibers is a very common technical problem. The difficulty of predicting the properties of paper products produced from heterogeneous sources puts several limitations, which therefore lead to severe economic losses and only a comprehensive characterization will enable their better utilization." [28]. These issues are not addressed by models in academia but software in industry has been trying to cover them. We consequently put forward the following propositions:

Proposition 4: *Integration of different influential aspects and disciplines like quality, manufacturing, fiber mechanics, packaging, and logistics are needed in order to improve the effectiveness, efficiency, and consistency in the production and prediction of corrugated board and box properties.*

Proposition 5: *Using robust design simulation of boxes contributes to an industrial strategy to deal with modeling, simulation, and quality of corrugated board and box as a long-standing problem.*

6 CONCLUDING REMARKS

In total, 18 models and four software programs for corrugated box design are identified in this research. Eight of the models use paper properties for predicting board properties while ten models predict corrugated box properties. The applicability of the models and software is different for the various supply chain actors (see Figure 6). In order to decrease the gap between theory and practice new insights, in the form of propositions toward improving the use and development of models and software for corrugated box design, are suggested. A holistic perspective for modeling corrugated board and box is proposed and enables practitioners and researchers to identify causes of variation in predictions by considering control and noise factors.

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Contact: Vahid Sohrabpour
Lund University, Faculty of Engineering, Department of Design Sciences, Packaging Logistics
P.O. Box 118, SE-221 00 Lund, Sweden
Email: vahid.sohrabpour@design.lth.se
URL: http://www.plog.lth.se

Vahid Sohrabpour is a PhD student at the Department of Design Sciences. His research interests include humanitarian logistics and product and packaging design and development.

Daniel Hellström is an Assistant Professor of Packaging Logistics at the Department of Design Sciences. His primary research interest is on interactions between Packaging and Logistics. He participates in several international research projects and teaches master students and executives.