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An investigation of critical factors in medical device development through Bayesian networks

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ABSTRACT

In this paper, we investigate the impact of product, company context and regulatory environment factors for their potential impact on medical device development (MDD). The presented work investigates the impact of these factors on the Food and Drug Administration's (FDA) decision time for submissions that request clearance, or approval to launch a medical device in the market. Our overall goal is to identify critical factors using historical data and rigorous techniques so that an expert system can be built to guide product developers to improve the efficiency of the MDD process, and thereby reduce associated costs. We employ a Bayesian network (BN) approach, a well-known machine learning method, to examine what the critical factors in the MDD context are. This analysis is performed using the data from 2400 FDA approved orthopedic devices that represent products from 474 different companies. Presented inferences are to be used as the backbone of an expert system specific to MDD.

1. Introduction

Although advances in technology has provided many indispensable medical products to improve human health and sustain it, the development cost of medical devices burdens the healthcare systems as the industry is more technology-centric than ever before. Accordingly, the identification of critical success factors for medical device development (MDD) has become increasingly important. These critical factors should be identified so that device development can be managed to minimize the adverse effects of these factors.

Many factors are related to the likelihood of success of devices in the market; and based on a company's ability to react to them, these factors are considered to be either internal or external (Medina, Okudan Kremer, & Wysk, 2012). Internal factors mostly focus on the organizational context within which design is executed, and among others these factors include organization's composition in terms of the level of experience in design teams (Lucke, Mickelson, & Anderson, 2009) and effective communication of the development priorities (Brown, Dixon, Eatock, Meenan, & Young, 2008). Likewise, several publications (Brown et al., 2008; Millson & Wilemon, 1998; Rochford & Rudelius, 1997) report that the execution of a complete development process that includes preliminary market analyses, financial analyses, and customer involvement is critical for the further commercial success of medical devices.

On the other hand, external factors are mostly related to costs and profits, research and development (R&D), clinical research and insurance companies' reimbursement (Advanced Medical Technology Association, 2003). Intellectual property protections and overseas market opportunities are also among these external factors. More importantly, the Food and Drug Administration (FDA), regulatory agency of medical devices marketed in the Unites States, has been suggested as the primary external factor influencing the development priorities (Advanced Medical Technology Association, 2003).

Success factors in product development have been examined in various ways thus far. However, existing methods used for the identification of critical success factors have a number of shortcomings; among these are the subjectivity of survey-based studies and the complexity to comprehensively and rigorously address both internal and external factors (Medina et al., 2012). This paper discusses these shortcomings and proposes to overcome them with the application of a Bayesian network (BN) approach to examine the impact of product characteristics, company context and regulatory environment related factors on MDD.

BN is a well-known method used for machine learning. Furthermore, it has been cited in the literature as a preferred method to address the limitations of other analysis methodologies (e.g., Kim & Park, 2008; Venter & Van Waveren, 2007). The BN approach allows for a scientifically objective analysis with the ability to

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simultaneously consider quantitative and qualitative data (Chiang & Che, 2010; Venter & Van Waveren, 2007).

In the paper, we use the BN approach to investigate the critical factors of MDD. BN analysis is performed using data from 2400 FDA approved orthopedic devices. In the remaining sections of the paper, we first provide a summary of the reviewed literature to identify potential factors with implications on MDD; then, we introduce the methodology. Details about the data set and results follow before we provide conclusions.

2. Literature review

The design, development and manufacture of medical devices is challenged with the requirements from regulatory agencies, such as FDA. This fact is considered to set MDD apart from generic new product development (NPD). However, investigations of critical factors for MDD have been similar to those of generic products for which survey-based studies were conducted to separately examine internal and external factors (e.g., Advanced Medical Technology Association, 2003; Brown et al., 2008; Ernst, 2002; Millson & Wilemon, 1998; Rochford & Rudelius, 1997). An exception to the predominant choice of using surveys is Lucke et al.'s (2009) work, which followed multiple years of device developments in order to show the relevance of the development team's experience as an internal factor with implications for development time, a performance measure.

In order to address the shortcomings of survey-based studies and the time constraints of following the complete development process, prior research efforts employed statistical methods (e.g., ANCOVA) to explain important factors in relation to FDA's decision time (Medina et al., 2012). However, this analysis did not allow for a holistic study of quantitative variables that were related given that variables with strong correlations should not be included together in the ANCOVA analysis. Accordingly, in this paper BN approach is selected for a more robust analysis, where both internal and external factors are considered.

BN was applied in the area of new product development (NPD) as a technique for decision-making support. For example, in response to the shortcomings outlined above and others, BN has been used to develop a decision framework that can (1) manage quantitative and qualitative data simultaneously, (2) provide input for the several stages of the development process, and (3) integrate multiple aspects in one visual model (Venter & Van Waveren, 2007). Accordingly, a decision support model was built to incorporate expert knowledge and perform what if analyses that would support decision makers taking actions within an NPD process.

The NPD risks and uncertainties are major concerns, for which BNs have helped to assess these risk factors (Cai, Sun, Si, & Yannou, 2011; Chiang & Che, 2010; Chin, Tang, Yang, Wong, & Wang, 2009). Some of the considered risk items include the time-to-market, manufacturability, maintainability and expected revenue of new products (Chiang & Che, 2010). The consideration of risks is a major issue for MDD, where the design of risk mitigation strategies is used to reduce the medical use error. This includes the development of the Bayesian risk identification model (BRIM) to manage and mitigate the risks related to human response failures that could come from a combination of interface, environment, or contextual influences (Rieger & Rahimi, 2011). BRIM defines performance-influencing conditions as the root causes that relate to the probability of human response failures. The result focusing on product interface design is a user error likelihood that can be used to assess product performance in terms of human interaction. While BRIM impacts the design stage of MDD, other efforts have been focused on the assessment of risk for devices already released to the market. At this stage, issues in the manufacturing process or supply chain have been addressed proactively with a BN based approach for the Health Hazard Analysis (HHA) (Jiang, Herzog, Pepin, & Baca, 2011). The results from this analysis are used by industry to perform corrective actions in the field, in addition to being considered by FDA for the classification of device recalls.

A different use of BN in medical device applications is the cost-effectiveness analysis of MDD. This analysis has been improved with a BN based approach of iterative economic evaluations of new medical device technologies throughout their development process (Vallejo-Torres et al., 2008). These iterative evaluations included the implementation of simple analyses at early stages that will become more robust by incorporating more evidence as the development process moves forward (Vallejo-Torres et al., 2008).

In general, the reviewed studies have shown successful implementations of BN, establishing BN to be a robust technique. At the same time, as summarized, there are studies that investigated the critical factors in MDD; although they are either not comprehensive (i.e., omitted consideration of external and internal factors simultaneously), or the nature of the survey methods and analytical techniques implemented limit the ability to generalize. Accordingly, as our first step on route to developing an expert system to aid medical device developers, we have devised the following methodology to investigate the critical factors relevant to the MDD context.

3. Data and variables

Data availability was dependent on the number of approved orthopedic devices in the FDA's public database to date. As a consequence, the raw data did not have an equal number of samples per category, i.e. product codes[1]. From the complete data set of 9013 orthopedic devices (from 166 product codes), some product codes only had one datum point while others had hundreds of data points. Only a subset (24) of these product codes was found to consistently have more than 100 data points for each code. In order to account for equal representation and hence to limit undue bias, we have randomly selected 100 devices per product code and included them along with their full FDA dataset. As a result, 2400 FDA approved orthopedic devices were randomly selected to study the critical factors of MDD.

Table 1 summarizes the variables under study with a description of their meaning. Note that the information contained in the table was a deduction of our review of the literature (presented in Medina, Okudan Kremer, and Wysk (2013), Medina, Wysk, & and Okudan Kremer (2011), Medina et al. (2012)) as well as an evaluation of the FDA data and how the available data could be used to represent factors cited in the literature. As can be observed in the table, for each variable we have listed if it is an internal- or external-variable, and quantitative- or qualitative-variable; we have also associated each variable either to the product, to the company or the regulatory environment (FDA). This association assignment process was done in an *ad hoc* manner. The variables were classified to be internal or external depending on the applicant's ability to influence such a factor. For instance, variables related to the regulatory environment (e.g., FDA's decision time and classifications) are not under the control of the applicant company. At the same time, product specific characteristics (e.g., context of use, body part, function) are under the control of the applicant company given their absolute power on the products they decide to develop and manufacture.

The variables were also classified given their direct association to the product, company or regulatory environment (FDA). The

[1] Product codes are FDA classifications used to group medical devices with the same characteristics and requirements.