Clinical decision support systems for personalized healthcare

Levente Kovács, György Eigner
Research and Innovation Center of Obuda University
John von Neumann Faculty of Informatics
Physiological Controls Group
Obuda University, Budapest, Hungary
Email: {kovacs.levente,eigner.gyorgy}@nik.uni-obuda.hu

***Abstract*—Clinical decision support systems (CDSS) are indispensable parts of individualized healing and therapy. Although several solutions exists, none of them could exploit the opportunities of modern healthcare devices due to the lack of information integration from these instruments. In most of the cases the available CDSS are data-based systems with clearly determined use-cases, but without patient models. The paper reviews theoretically feasible CDSS with data- and model-based properties for better personalized healthcare outcome. Such an integrated system collects all available patient data collaborating with the individualized mathematical models; hence, could reach better results in making decisions and predictions about the actual and future state of the patient. Specific challenge to be solved focuses on the synchronization of the operations with the healthcare professionals providing useful assistance for the patients. At the end, two concrete examples are discussed based on the presented aspects: control of anesthesia and glycemic control in Intensive Care Units.**

I. Introduction

Decision support systems (DSS) are computer based systems that supports decision-making processes [1]. Systems which might support decision making are classified as DSS as well [2]. The investigation of application roles of DSS dates back to the 1970s [3], but they still provide research possibilities. Many guidance and survey can be found in the topic [4]. The first applications were business and management related [5], nevertheless they are applied widely nowadays, being included in agriculture, traffic control or medical problems [6]–[8]. The mostly researched field represents today the medical decision support being especially important in the age of internet of things and healthcare personalization.

The most common taxonomy for DSS is based on [4] and can be distinguished in the followings:

- Communication-driven DSS;
- Data-driven DSS;
- Document-driven DSS;
- Knowledge-driven DSS;
- Model-driven DSS.

From medical application point of view the advantageous classes are data-driven, knowledge-driven or model-driven DSS. The knowledge solving DSS uses the accumulated information in a particular domain (in present case the given medical field/disease) resulting by the evaluated data to a given action.

In medical field staff must record certain events that can be used to recover some necessary (personalized) information [9]. If the storage of these information is web-based, it cannot support only work at a certain clinic, but world widely in a cloud [10]. Hence, two problems could appear: the amount of available information makes it hard to handle them, or the information are unstructured. For the first problem data mining solutions can be applied. However, the lack of structure can still prohibit the effective decision making. This is why some kind of structuring, modeling of information, need to be applied focusing on model-based medical data handling [11], [12].

The current paper reviews how a DSS can be designed for clinical application, considering personalized health requirements. The benefits of knowledge-driven and model-driven DSS are combined focusing on web-based interclinical knowledge share and model-based engineering possibilities. The paper details the necessary steps and components (e.g. creation of subsystems, environment considerations). The theoretical aspects are highlighted on two application fields: control of anesthesia and support of glycemic control.

II. CDSS for personalized healthcare

In this section we give a general description of a feasible DSS which could be used supporting medical staff in taking more precise estimates about the patients' actual and future conditions, and the necessary operations to reach an optimal solution in patient care.

The following key features are necessary during the development of a model-based CDSS system:

- Utilization of the required environment;
- Delimiting the indispensable subparts of a model-based CDSS;
- Modeling questions;
- Available data sources;
- Running environment;
- Usability questions.

These can be defined as milestones for the CDSS as well and we give more details on each of them in the followings.

A. Utilization of the required environment

The first step in a CDSS design is to decide the environment on what we want to operate our system. Determining the feasibility borders of the system is not a trivial task. Hospitals have several departments which can be divided into different categories. The main parts that are independent from the departments and from the patient care viewpoint are the surgical environments and the therapeutic environments [13], [14].

The definition of a *surgical environment* is clearly defined: sterile spaces divided in patient, medical staff, medical tools and devices parts where the active interventions take place [15]. While there is no unequivocal definition of therapeutic spaces, intensive care units (ICU), visiting areas, etc., belong in this group.

When developing a CDSS system, the operational environment determines who and how could use the system, what are the important indicators, what are the necessary and the available data ([16]). In a surgical environment obviously much more patient data can be collected since the medical staff deals with a given patient; hence, the medical devices record and visualize the vital signs of that patient. As a result, quality aspects of available resources can be increased ([7]).

In a *therapeutic environment*, the spectra of available resources are wider. In ICU almost every medical device gives vital signs recording possibility [17], but as the medical staff is limited safety regulations and precise monitoring aspects should be included. In therapeutic environments outside ICU the patient monitoring possibilities are more limited due to their less critical nature [14].

B. The model-based CDSS

A model-based CDSS can be devided in the following main parts:

- Appropriate subsystems;
- Data transformer subunit;
- Running environment.

However, a highly developed model-based DSS consist not only a modeling subsystem. In most of the cases, the model driven approaches have data-driven, knowledge-driven subsystem parts as well [11]. This is the consequence that for building up, operating and controlling a model all necessary data need to be collected giving accompanying explanation of the them.

In a CDSS the data could recovered from diverse sources. Hence, during the development of the CDSS it is important to transform all collected data (e.g. vital signs from medical devices; medical staff's observations) and connected explanations (e.g. drug effect and dosing; necessary steps to stave off an arising clinical emergency situation) into unified data and knowledge subsystem. Thus, the models in the model subsystem can be adapted using the data subsystem, while the necessary information could taken from knowledge subsystem. Obviously, in some cases data could be the necessary information itself (e.g. actual heart rate frequency).

In a model-based situation the formalized data and knowledge subsystems represent accessories of the model-based subsystem. Therefore, these subparts are reduced and contain only those information which are strictly connected to the modeling tasks. Consequently, the data subsystem should contain every required data for modeling, while the knowledge subsystem should consist every information about the models, modeling tasks, modeling purposes, required additional data and the ability to transform these to usable form. In this way, the important information produced by modeling are quickly understandable and usable. For this purpose the usual solution is to create a unique ontology to be used only by the given CDSS [18].

An essential part of the core system is represented by the data transformer subunit. In CDSS systems data are collected from diverse data sources. Hence, they should be transferred into a directly usable form, which could be a standardized one (like XML, or XML-based formats) or individually defined data structures. Both solutions have their advantages and disadvantages. If a CDSS uses a standardized data structure, the communication between the external systems could be easier, the standards contain the necessary requirements and regulations and the development may become faster. However, if a CDSS uses an individual data structure, the developer can establish a more closer/safer system and every sensitive data will be under direct control. As a result, the safety of the system could be higher.

The running environment provides the core of the system, determines the abilities and possibilities of the system (see Section II-E).

Fig. 1. shows the basic structure of a model-based CDSS with its essential sub-parts.

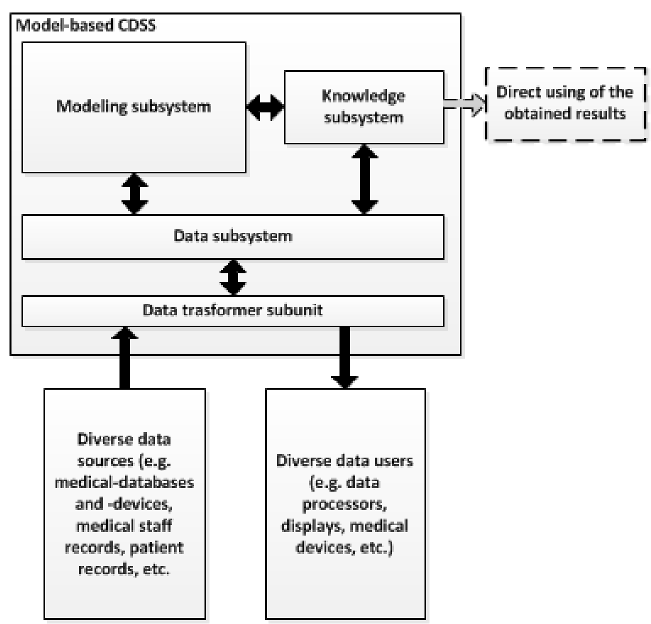

Figure 1. The schematic structure of a model-based CDSS with its composed subsystems.

C. Modeling questions

Nowadays, personalized healthcare has several definitions and meanings. Strictly, the medical staff gives all the time personalized treatment and drug delivery by the given patient condition's particularities using the patient's data (results of investigations, past conditions, chronic diseases, etc.). Popular definition is the genetic based one: the healthcare is personalized, if the medical staff uses the genetic information of the patient and provides care based on that [19], [20].

From modeling point of view personalization means that the mathematical model describes the patient's given health phenomena / disease with given constraints. To reach this condition it is necessary to adapt the patient's own data on the generally set mathematical model, or if no model then to identify it based on the collected data. After the model is personalized and/or identified, it can be used for simulating different treatment protocols. This is known as in silico tests or virtual patient validations.

Further, from control perspective this "personalized model" can be used in control algorithms design, like studying the given unoriginal behavior of the patient, make parallel tests with the evolution of the real patient's condition. The latter is the prerequisite idea of using for example Model Predictive Control (MPC), one of the mostly used control concept in model-based healthcare nowadays [21], [22]; however this concept may be used to realize other control algorithms as well [23].

A model-based CDSS can be formalized to provide a running environment of these models. Thus, the Model subsystem of a CDSS primarily should handle modeling and identification. If the CDSS is used to control the patient's given characteristic then beyond satisfying the control tasks it should be able to give advises on realizing the control goals.

Fig. 2. represents a schematic structure of a system with the mentioned properties.

The purpose of a CDSS determines the type of the model needed. For example, if the CDSS purpose is to support surgical anesthesia, then anesthetic models should be implemented. In every case, before the model selection feasibility analysis is needed. If the goal is only to predict the change of a patient's characteristics, modeling and identification is enough.

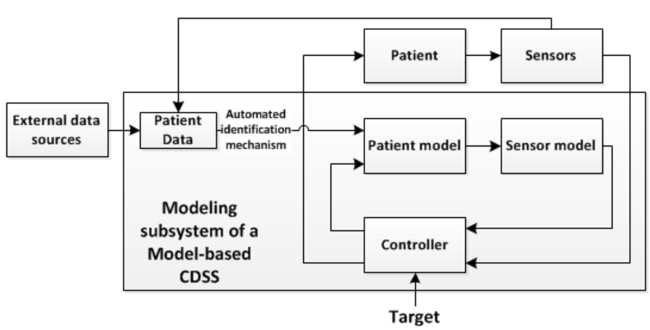

Figure 2. Possible control structure of the Modeling subsystem part of a model-based CDSS.

In this case, several identification methods can be used, but it should be on the complexity of the model and the available patient data. As every patient has unique parameters and these can change during the care, online data monitoring and online automated identification methods can ensure achieving the best results and lead to the personalized care. Obviously, if the circumstances are not given, other solutions (e.g. offline identification, identification based on preliminary data, etc.) can be used, but in this case, tight observation and critical handling of the results are needed [24].

If the CDSS purpose is to provide decision support based on model-based control of the patient's characteristics, then this should be taken into consideration during model selection and control algorithm design as well. A practical solution of the problem represents the object-oriented, agent-based approach, when the model is handled as runnable object (as an agent) [25].

D. Available data sources

Several data sources are available to supply a CDSS system depending on the environment of the CDSS. Independent data sources are the followings:

- Hospital Information System (HIS) or Electronic Health Record (EHR) database: these systems can provide offline patient data (from the CDSS's actual operation point of view) giving important feedback on the patient's condition;
- Immediately recorded data by the medical staff: result of a hand-made investigation, like actual blood pressure; it can be on- and off-line as well;
- Patient feedback: if the situation lets, a patient could indicate its own condition.

Medical devices and sensors can record the patient data automatically and use them not just as passive records, but transmit and store activities (e.g. dosed drug amount) for model-based control purposes. Operating rooms and ICUs have numerous tools for patient monitoring; however, a nursing home has less monitoring possibilities. For example, a model-based CDSS supporting control of anesthesia in surgical environment requires the patient EEG (for bispectral index), ECG, neuromuscular blockade (NMB) monitoring, and other parameters. On the other hand, a CDSS supporting short-term tight glycemic control (TGC) for long term optimization of blood glucose levels may require only (but continuously) glycemic parameters [26]–[30].

E. Running environment

The realization environment of the system is a key question in the field of CDSS. Two options are available here:

- web-based running environment;
- non web-based running environment.

Web-based running environment is a convenient solution for the developers. Several highly developed and occasionally open-source tools can be built in a CDSS, from the web-browsers-based runtime platform to the client devices: computer terminals, smartphones, tablets, etc.

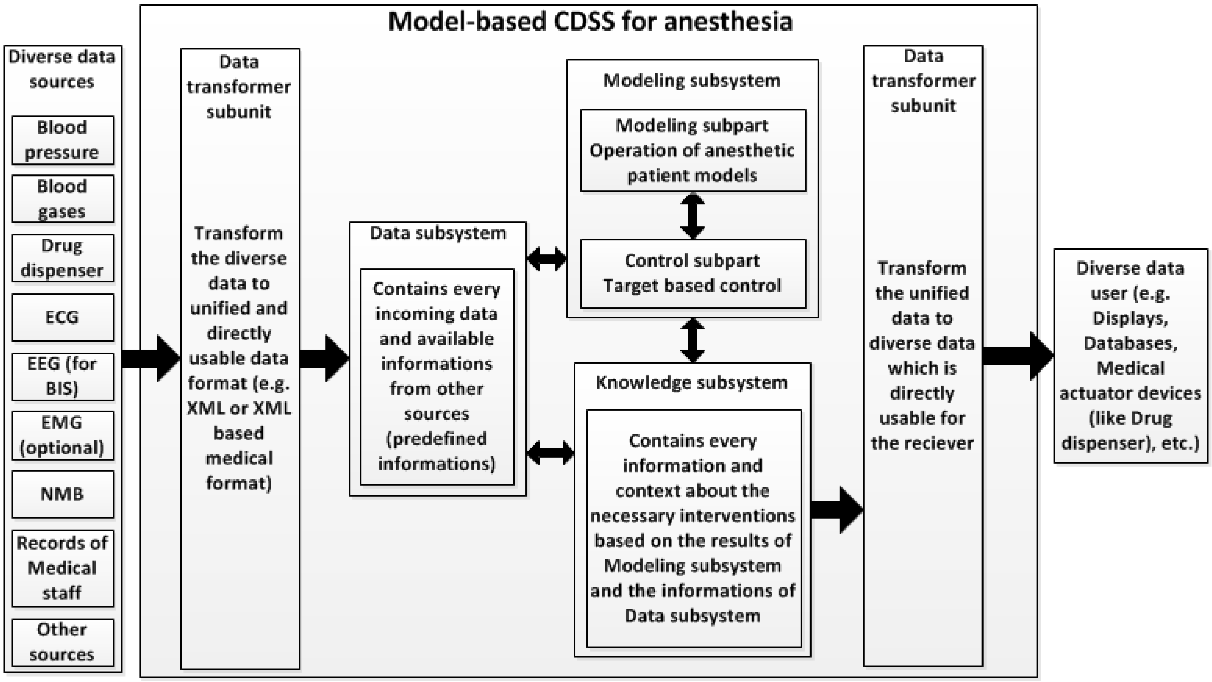

Figure 3. Concrete example of model-based CDSS system to support anesthesia.

This solution provides an easy to use, cheap, standardized, flexible, extensible and interoperable system. However, the largest problems of a web-based CDSS consists in solving its availability (permanent online access), integration (collaboration with other systems, like hospital information system (HIS), or electronic health record (EHR) database) and on top of them, the data safety (safety handling of sensitive health data) [31], [32]. To develop it, the following tools are needed:

- Web supporting operating system;
- Webserver;
- Content manager;
- Database manager;
- Appropriate language.

Non web-based solutions give the chance to create a uniquely closed system running on a computer terminal or on a central server. In this closed environment, without the web-based constraints a more secured system can be developed, but there is still a high risk of its availability (one or few systems are running on local servers; hence, access is possible only from the given local network). Obviously, it is possible to connect the local CDSS to other systems as well (even trough the Internet) providing it some degree of flexibility [33].

F. Usability questions

Usability is a critical question in CDSS which is mostly determined by its purpose and the running environment. During the CDSS development general software ergonomic criterias should be followed: easy to use, convenient, logical graphical user interface (GUI), flexibly and adaptability on other available platforms.

Moreover, it is needed to consider new challenges supported by mobile and wearable devices. These tools facilitate the access of CDSS; although, data safety should more critically envisaged.

G. Two possible examples of model-based CDSS

In the followings, we exemplify the usability of a Model-based CDSS by two different cases. First, we show how it may build up such a system in surgical environment to support the medical staff in the control of anesthesia. The second example will be a system with wide-range usability for TGC control in ICUs.

1) Model-based CDSS to support control of anesthesia in surgical environment: Fig. 3 shows the schematic structure of a complex, model-based CDSS system to support the control of anesthesia at surgical environment. On the figure one can see the available data sources (devices and sensors), data transformer subunits (to convert diverse data to unified ones), data subsystem (to contain every necessary data), knowledge subsystem (to contain every relations, information about the data and results of modeling subsystem) and modeling subsystem (to realize the modeling and control units).

2) Model-based CDSS to support glycemic control in several environments: TGC can be used at several hospitalized spaces with different purposes. Glycemic control has several benefits in short and long term as well (promoting healing after surgery, decreasing the chance for inflammation, providing better glycemic characteristics for diabetic or pre-diabetic patients, etc.). In ICUs the TGC has absolute relevance ([34]). Glycemic control is important at neonates and elderly patients, but needs different approaches. The usual nursing environment may be different as well [24], [34]–[36].

Fig. 4 shows the schematic structure of a TGC supporting CDSS.

III. Conclusion

The goal of the current paper was to give a review on the model-based clinical support systems. We have shown the basic concept, the structure and the necessary parts of such a system, and we have presented the ideas to be considered during the development of a CDSS. We have demonstrated that these systems could have wide range usability and could support decision making in several clinical environments. To illustrate the CDSS concept we have given two examples of the model-based CDSS: one focusing on general anesthesia and one focusing on tight glycemic control with different purposes in ICUs.

Acknowledgment

L. Kovács thankfully acknowledge the support of the János Bolyai Research Scholarship of the Hungarian Academy of Sciences. Gy. Eigner was supported by the Robotics Special College of Obuda University. The research was also supported by the Research and Innovation Center of Obuda University.

References

[1] P. Keen, *Decision Support Systems: A Research Perspective*. Center for Information Systems Research, Sloan School of Management, Massachusetts Inst. of Technol., Cambridge, MA, USA, 1980.

[2] J. Sprague, R.H., "A framework for the development of decision support systems," *MIS quarterly*, vol. 4, no. 4, pp. 1–26, 1980.

[3] J. Shim, M. Warkentin, J. Courtney, D. Power, R. Sharda, and C. Carlsson, "Past, present, and future of decision support technology," *J Dec Sup Syst*, vol. 33, pp. 111–126, 2002.

[4] D. Arnott and G. Pervan, "Eight key issues for the decision support systems discipline," *Dec Sup Syst*, vol. 44, no. 3, pp. 657–672, 2008.

[5] S. Ritchie, "A knowledge-based decision support architecture for advanced traffic management," *Transp Res*, vol. 24, no. 1, pp. 27–37, 1990.

[6] P. Cox, "Some issues in the design of agricultural decision support systems," *Agr Sys*, vol. 52, no. 2, pp. 355–381, 1996.

[7] A. McCoy, G. Melton, A. Wright, and D. Sittig, "Clinical decision support for colon and rectal surgery: An overview," *Clin Colon Rectal Surg*, vol. 26, no. 1, pp. 23–30, 2013.

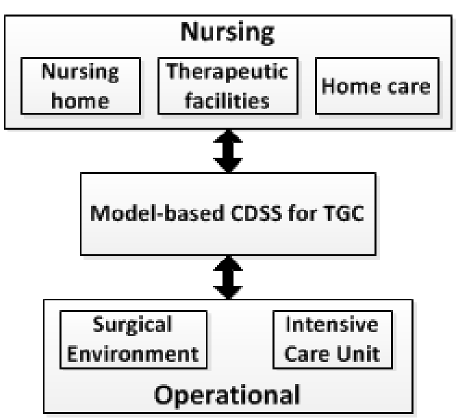

Figure 4. Model-based CDSS system for TGC realization with different purposes.

[8] D. Power, *Decision Support Systems: Concepts and Resources for Managers*. Quorum Books division Greenwood Publishing, Santa Barbara, CA, USA, 2002.

[9] P. Kavitha and T. Sasipraba, "Knowledge driven healthcare decision support system using distributed data mining," *Indian J Comp Scien and Eng*, vol. 3, no. 3, pp. 464–469, 2012.

[10] D. Power and S. Kaparthi, "Building web-based decision support systems," *Studies in Inf and Contr*, vol. 11, no. 4, pp. 291–302, 2002.

[11] D. Power and R. Sharda, "Model-driven decision support systems: Concepts and research directions," *J Dec Sup Syst*, vol. 43, pp. 1044–1061, 2007.

[12] J. Mathe, A. Ledeczi, A. Nadas, J. Sztipanovits, J. Martin, L. Weavind, A. Miller, P. Miller, and D. Maron, "A model-integrated, guideline-driven, clinical decision-support system," *IEEE Software*, vol. 26, no. 4, pp. 54–61, 2009.

[13] W. Charney, *Handbook of modern hospital safety*, 3rd ed. Harrisburg, PA, USA: Morehouse Publishing, 1984.

[14] L. Reimer and J. Wagner, Eds., *The Hospital Handbook: A Practical Guide to Hospital Visitation*, 2nd ed. Boca Raton, FL, USA: CRC Press, 2010.

[15] A. Weiss and A. Elixhauser, *Trends in Operating Room Procedures in U.S. Hospitals 2001-2011*. Rockville, MD, USA: Agency for Healthcare Research and Quality, 2014.

[16] A. Garg, N. Adhikari, H. McDonald, M. Rosas-Arellano, P. Devereaux, J. Beyene, J. Sam, and R. Haynes, "Effects of computerized clinical decision support systems on practitioner performance and patient outcomes," *JAMA*, vol. 293, no. 10, pp. 1223–1238, 2005.

[17] WHO, *WHO Integrated Management for Emergency and Essential Surgical Care (IMEESC) Tool Kit*. Online document, Available (2015): WHO, 2009.

[18] D. Gasevic, D. Djuric, and V. Devedzi, *Model Driven Engineering and Ontology Development*, 2nd ed. Heidelberg, Germany, EU: Springer-Verlag, 2009.

[19] W. Redekop and D. Mladsi, "The faces of personalized medicine: A framework for understanding its meaning and scope," *Val Health*, vol. 16, pp. S4–S9, 2013.

[20] FDA, *Paving the Way for Personalized Medicine*. Online document, Available (2015): FDA, 2013.

[21] L. Grune and J. Pannek, Eds., *Nonlinear Model Predictive Control*, 2nd ed. London, GB, EU: Springer-Verlag, 2011.

[22] C. Cobelli, C. Dalla Man, G. Sparacino, L. Magni, G. de Nicolao, and B. Kovatchev, "Diabetes: Models, signals and control," *IEEE Rev Biomed Eng*, vol. 2, pp. 54–96, 2009.

[23] P. Rezaei, K. Rezaie, S. Nazai-Shirkouhi, and M. Tajabadi, "Application of fuzzy multi-criteria decision making analysis for evaluating and selecting the best location for construction of underground dam," *ACTA Pol Hun*, vol. 10, no. 7, pp. 187–205, 2013.

[24] C. Pretty, A. Le Compte, J. Chase, G. Shaw, J. Preiser, S. Penning, and T. Desaive, "Variability of insulin sensitivity during the first 4?days of critical illness: implications for tight glycemic control," *Ann Intensive Care*, vol. 2, no. 1, p. 10, 2012.

[25] S. Wilk, W. Michalowski, D. O'Sullivan, K. Farion, J. Sayyad-Shirabad, C. Kuziemsky, and B. Kukawka, "A task-based support architecture for developing point-of-care clinical decision support systems for the emergency department," *Methods Inf Med*, vol. 52, no. 1, pp. 18–32, 2013.

[26] H. Kwok, D. Linkens, M. Mahfouf, and G. Mills, "Siva: a hybrid knowledge-and-model-based advisory system for intensive care ventilators," *IEEE Trans Inf Technol Biomed*, vol. 8, no. 2, pp. 161–172, 2004.

[27] C. Schurink, P. Lucas, I. Hoepelman, and M. Bonten, "Computer-assisted decision support for the diagnosis and treatment of infectious diseases in intensive care units," *Lancet Infect Dis*, vol. 5, pp. 305–312, 2005.

[28] B. Gholami, J. Bailey, W. Haddad, and A. Tannenbaum, "Clinical decision support and closed-loop control for cardiopulmonary management and intensive care unit sedation using expert systems," *IEEE Trans Control Syst Technol*, vol. 20, no. 5, pp. 1343–1350, 2012.

[29] G. Alexander, "Analysis of an integrated clinical decision support system in nursing home clinical information systems," *J Gerontol Nurs*, vol. 34, no. 2, pp. 15–20, 2008.

[30] M. Fossum, Ed., *Computerized decision support system in nursing home*. Online document, Available (2015): Orebro University 2012, 2012.

[31] A. Wicht, G. Meixner, and U. Klein, "Design and prototypical development of a web based decision support system for early detection of sepsis in hematology," in *Proceedings of the 1st International Workshop on Engineering Interactive Computing Systems for Medicine and Health Care*. ACM, 6 2011.

[32] H. Bhargava, D. Power, and D. Sun, "Progress in web-based decision support technologies," *J Dec Sup Syst*, vol. 43, pp. 1083–1095, 2007.

[33] M. Michel, J. Trafton, and M. S., "Improving patient safety using athena-decision support system technology: The opioid therapy for chronic pain experience," *Techn Med Safety*, vol. 4, pp. 1–12, 2008.

[34] X. Wing, J. Chase, G. Shaw, T. Lotz, J. Lin, I. Singh-Levett, L. Hollongsworth, O. Wong, and S. Andreassen, "Model predictive glycaemic regulation in critical illness using insulin and nutrition input: a pilot study," *Med Eng Phys*, vol. 28, no. 7, pp. 665–681, 2006.

[35] C. Thorpe, W. Gellad, C. Good, S. Zhang, X. Zhao, M. Mor, and M. Fine, "Tight glycemic control and use of hypoglycemic medications in older veterans with type 2 diabetes and comorbid dementia," *Diab Care*, 2015.

[36] M. Signal, R. Gottlieb, A. Le Compte, and J. Chase, "Continuous glucose monitoring and trend accuracy: news about a trend compass," *J Diab Sci Technol*, vol. 8, no. 5, pp. 986–997, 2014.