10-2022

A Method to Visualize Patient Flow Using Virtual Reality and Serious Gaming Techniques

MIchael Scott Or

Andrew Hoque

Carolyn McGregor

1. A Method to Visualize Patient Flow Using Virtual Reality and Serious Gaming Techniques

Michael Scott Orr
Ontario Tech University
Michael.Orr3@ontariotechu.net

Andrew Hogue
Ontario Tech University
andrew.hogue@ontariotechu.ca

Carolyn McGregor
Faculty of Business and IT, Ontario Tech University
Faculty of Engineering and IT, University of Technology Sydney
c.mcgregor@ieee.org

Abstract

This paper proposes a method to visualize Emergency Department patient flow data in a Virtual Reality (VR) Serious Game (SG) environment. Visualizing the patient flow data will allow patterns and trends that hospitals can use to reduce alternative level of care (ALC) days and increase the acute capacity of the hospital. The method proposes to use Unity to develop two VR visualisations of patient flow to a hospital ED such that hospital staff can determine which of the two visualizations will be the most usable, immersive, and playable. This paper also presents future work that will look at the whole system of a hospital using one years' worth of patient flow data to develop a usable, immersive and playable Virtual Environment (VE).

Keywords: Usability, Data Visualization, Serious Gaming, Big Data, Virtual Reality, Unity.

1. Introduction

One of the most important key performance indicators in the Emergency Department (ED) is wait-times. Wait-times are affected by patient flow in and out of ED. There is an expectation that patients will not be staying in ED for extended periods of time waiting for their next steps in their care journey. ED design typically expects a patient's length of stay to be between two to three hours. Between 2013 and 2014 the ED's across Canada saw 10 million visits consisting of approximately 23% under the age of 19, 59% between 19 to 64 and 21% greater than 64 (CIHI & NACRS, 2014). Of the over 64 age group, 14% required admission to the hospital and waited 10 to 12 hours for the decision to be admitted. Once the decision to admit the patient is made, the patient has typically waited between 25 to 27 hours for an inpatient bed to become available (CIHI & NACRS, 2014). When it is necessary for a patient to be admitted, there is an additional burden on the ED of 2.5 times more care required to continually care for the patient until the inpatient bed becomes available (Drummond, 2002). Wait-time in ED is one of the most important factors affecting ED patient flow and efficiency (Sinclair, 2007). There are several contributing factors that compound the waiting time of patients who need to be admitted including lack of appropriate beds, shortage of staff specifically nurses, increase in complexity, acuity, treatments, volumes, appropriate discharge care and facilities to handle patient care (Drummond, 2002). A key identified area that impacts ED patient flow and efficiency in Canada is the lack of inpatient beds. With only 2.52 acute beds per 1000 in 2019, Canada is ranked 31 out of 38 in Organization for Economic Co-Operation and Development (OECD) (OECD, 2013; Organization for Economic Co-Operation and Development, 2019). Canada acute inpatient bed occupancy is fourth at 91.6% the highest in 2019 compared to other OECD countries (Organisation for Economic Cooperation and Development (OECD), 2021). Another contributing factor to the lack of inpatients beds and high occupancy are long wait-times for patients ready to be discharged to Alternative Levels of Care (ALC) beds such as long-term care, rehabilitation, assisted living or community care (Affleck et al., 2012). ALC patients are accounting for 20% of the inpatient beds and are known as “bed blockers” (Drummond, 2002). By better understanding and visualizing where and how patients move through and out of the hospital, hospitals can identify bottlenecks and “bed blockers” as they occur and deal with active mitigation.

This paper presents a method that proposes to visualize patient flow using virtual reality (VR) and serious gaming (SG) technology using ED as the test case. We propose the design for initial usability testing to determine the most effective VR environment to visualize patient flow. The focus of the paper will be to provide examples of developed VR scenes of patient flow that can be used to determine which scene would be the most useable, immersive and playable. Unity (www.Unity.com), a game engine development environment, is an effective tool to use to develop a VR SG. The paper will detail usability and playability considerations for developing a VR SG. Considering usability and playability will ensure an immersive VR SG environment for end users to explore patient flow into, through and out of an ED. The paper will provide a proposal of a VR SG developed using Unity that will determine the most effective way to visualize patient flow in a virtual environment (VE). The paper also details future work to expand the work to include the complete VE of the patient journey through the hospital as a whole system.

2. Literature Review

Several methods to visualize patient flow have been previously proposed including dashboards, models and simulations. Dashboards typically present information as a grouping of charts and gauges that can be used to assess patient flow metrics (Buttigieg et al., 2017). Models illustrating the process of patients on their care journey have been used to detail patient flow (Mohiuddin et al., 2017). Simulations provide a model of patient flow that visually details the paths patients could take based on past information mathematically modelled (Clissold et al., 2015).

Henderson and Mason (2000) developed a user-friendly interface to a visualization of ambulance data to show current ambulance performance used to redesign and develop new and more efficient ambulance services (Henderson & Mason, 2000). Wang et al. (2008) performed a controlled usability study using a visualisation of data rendered in LifeLines2 that provides an environment to allow visualisation of temporal EHR data from many data sources (Wang et al., 2008). They found that clinicians’ response time to sentinel electronic medical record (EMR) events improved by 61%. The interface was found to be usable and intuitive for clinicians (Wang et al., 2008).

Two dimensional (2D) dashboards, models and simulation abstract or model operational patient flow but require expertise to interpret or use the associated software. Developing a VE using VR and SG principles of patient flow to the hospital, through their patient care journey and final discharge to an appropriate location has the potential to provide a more immersive three-dimensional (3D) environment. Hospitals can then more closely monitor their hospital ED and ALC patient flow performance. The VE must be developed to enable the hospital to view the VE not as a “game”, but an easy-to-use tool to examine patient flow into the ED. In Tsoy (2019) a SG was found to provide sufficient utility in teaching patient flow in the ED to physicians, nurses and students (Tsoy et al., 2019).

Big Data (BD) has experienced a large growth of data in healthcare. Both structured and unstructured data has grown from 500 petabytes in 2012 to an expected 25,000 petabytes in 2020 which can be attributed to the implementation of EMR computer systems (Feldman et al., 2012). BD is determined by data volume, velocity, variety, veracity and value known as the 5v’s (Laney, 2001). Data volume are large volumes of both structured and unstructured data contained in an organization and can include transactional, real-time streaming or even image data (Laney, 2001). Velocity is how fast the data is generated and consumed by an organization (Laney, 2001). Variety are the various format and data systems that are used within an organization. Veracity is the quality and trust level that an organization has of the data captured and used (Fosso Wamba et al., 2015). Finally, value is how useful and relevant the data is to the organization (Chen et al., 2014; Fosso Wamba et al., 2015; Gantz & Reinsel, 2011; Hashem et al., 2015). One of the key BD sets available in hospitals that are part of EMR's are Admission Discharge and Transfer (ADT) computer systems which capture the transactional patient flow from hospital admission to discharge along with all the changes of location the patient travels on their care journey. In addition to ADT the Discharge Abstract Database (DAD) and National Ambulatory Care Reporting, are BD sets that are supplied by the hospital to the government.

The freely available Unity game engine can handle large amounts of data that can be graphically visualized to expose patterns and trends (Djorgovski, 2012). Unity can scale large data sets (100, 000 data points) on modest hardware requirements (Djorgovski, 2012; Drechsler & Soeken, 2013). Challenges with working in Unity are to ensure the visualisation presents high density data sets in a way a user can readily view the exposed patterns. Drechsler and Soeken (2013) suggest that visualisation provides for "true-to-reality" rendering of data that can create a virtual world based on the data set used that has an intuitive feel that the end user can extrapolate to the real world (Drechsler & Soeken, 2013). Unity manages the physics of the virtual world and provides 3D asset creation and management that allow for efficient structuring of data into an effective visualisation.

2.4 Virtual Reality (VR) Usability

There are two main concepts that are used in VR to rate usability which are immersion and presence. Immersion can be viewed as the ability of a VR system to provide a sensory experience equivalent to the real-world experience (Slater, 2003). Iaha et al. (2014) define immersion as displays that can produce the same degree of realism and "sensory fidelity" we would experience in the real-world. With increasing fidelity of VR applications, sensory input will increase the level of immersion and corresponding sense of presence (Bowman et al., 2007).

Presence is about combining sensory data with perceptual processing in an environment to create a sense of "being there" (Slater, 2003). If presence is obtained in VR the user reacts to stimuli as if they were physically present in a real-world environment (Slater, 2003). Sutcliffe et al. (2004) describes presence as how "real or natural the user's experience" is in a VR environment (Sutcliffe & Gault, 2004).

2.5 Serious Gaming Usability

Zyda (2005) defines a serious game (SG) as "a mental contest, played with a computer in accordance with specific rules that uses entertainment to further government or corporate training, education, health, public policy, and strategic communication objectives" (Zyda, 2005). SG primary focus is to aid in the learning of a specific topic or domain (Adamo-Villani et al., 2013). For SG to enhance immersion, the environment must provide sensory input that creates a sense of presence(Zyda, 2005). Zyda (2005) suggests that the VR environment should faithfully represent the real-world to ensure that the user has a sense of presence this is specifically important for training applications (Zyda, 2005).

SG has been used in healthcare specifically for training and patient treatments. Graafland et al. (2012) undertook a systematic review of SG used in healthcare and found 25 articles indicating that SG is an innovative approach to education and training of medical professions (Graafland et al., 2012). Serious games and VR that implements realistic and adaptive environments have been shown to be beneficial, motivational and usable in healthcare. SG and Unity can be leveraged to create dynamic scenes using an accurate physics model that closely mimics the real world.

2.6 Serious Gaming Playability

Usability focuses on game functionality where playability requires a holistic view of game component integration combined with user experience (Olsen et al., 2011). Both usability and playability must be balanced to ensure a positive user experience along with delivering educational value requires that the user be engaged during the design and development of VR and SG VE (Olsen et al., 2011).

To conclude, the literature review motivates the need to design assessment of the developed VE for both usability and playability. Conducting usability assessment will ensure an immersive experience that is acceptable to the user. Assessing playability will confirm that user experience is positive and valuable.

3. Method to Visualize Patient Flow Using VR

This paper proposes a method to visualize patient flow using a VR and SG to create a VE. This method is instantiated within a demonstration of a patient flow simulation developed in Unity. To construct the method, we first considered the translation of data elements to components within a VR SG environment and subsequently determined the depth of immersion required to ensure the VR SG is usable and playable by the target users (i.e., healthcare administration and operational personal).

3.1 From Dataset to Serious Game Structure

The significant components required for the simulation data set in this context are the entities of healthcare facilities, modes of transportation and patient genders. Each of the entities have attributes that are either variable and require representation in the VE dataset or are fixed and whose information can be sourced from knowledge about the entities. For example, gender information can be variable based on the simulation data and would be represented within the dataset, but the attributes of a healthcare facility relating to the number of floors and locations of wards and bed spaces can be obtained from other sources and would not be represented in the dataset other than room numbers (See Table 1). Structural data can be obtained from architectural diagrams and from recording actual space layouts that would be recognizable by the users when rendered in VR.

Data Item	Data Item	Data Item	Data Item	Data Item
Encounter #	Admit/Discharge Decision from Emerg	Time Mental Health crisis worker called	Ward - start of ALC time/day	ED entry (Y/N)
Gender	Patient leaves ED time	Time Metal Health Crisis worker arrived	Ward Discharge time/day	CTAS (1-5)
Triage Time	Time Tests Ordered from ED (Labs, DI, imaging)	Medical Assess & Consult Unit entry time/day	Ward exit time/day	Surge status by date
Time entering ED treatment area	Tests Results Completed Time	Medical Assess & Consult Unit exit time/day	Exit/Discharge from Hospital	Service patient is admitted to (on-service)
Ambulance arrival time	Time consult called by ED	ICU entry time/day	Reason RFD not disch. (if several incl. date of change)	ED physician name (can be given a code)
Ambulance offload time	Time consult arrives to ED	ICU exit time/day	Patient Transfers OUT (to other facility) exit time	Number of ED consults
First ED physician contact time	Consult Service Called	Ward entry time/day	Tranfer IN (from other facility) Entry time	Service of consult (s)
ED disposition time and date (decision to admit or not)	Time CCAC contacted by ED	Ward - start of NRFD status time/day	Patient Arrival Day of week	ED consult name (s) (can be given a code)
Admit criteria met (ED patient)?	Time CCAC concludes ED patient status	Ward - start of RFD status time/day	Patient Arrival time of day	Date time of each ambulance consideration call

Table 1: Patient flow data set

The VR SG can be developed using realistic architecture, geographical locations, elements, time and metrics. Architecture can be visualized that closely resembles a hospital which may show a virtual ED layout that mimics reality.

The VE can be constructed to closely resemble the geographical location of the hospital with roads and buildings that are spaced proportionally as compared to reality. Elements are visual items that are built in the VE which would include people, vehicles, signs or equipment that closely resembles reality. Time can be changed for display of past conditions based on the dataset to allow review of conditions that existed during a specific period of time. Time can be adjusted to either slow down or speed up the review of the dataset in VE to allow the end user to view trends and patterns that might not be seen using 2D methods. Metrics from the dataset can be incorporated in the VE to provide details based on time, elements, process or tasks along with potential for heatmap views. Incorporating the dataset in VE the end user can play and replay events and processes that occurred in the hospital over time, which then can be used to examine conditions that affect patient flow to, through the hospital and to a final location. By using a VR SG that faithfully represents an environment that is familiar and intuitive, the user will be able to see trends and patterns along with patient care bottlenecks over a period of time and specifically focus on ALC patients. Using the developed VR SG in a 3D VE will provide an optimum visual of a hospital that is easily relatable to the end user who can then see trends and patterns over time that may be more difficult to detect using 2D methods. By utilizing this approach, we feel the end user will engage with this environment as a mental contest towards optimization and in so doing we believe that this has great potential to support improved efficiencies and reduce errors.

3.2 Scene Development

The scene development will focus on evaluating each scene's immersion and usability to determine if the scene conveys enough information that the end user can determine patient flow to the hospital. To ensure that invested development time is not wasted on complete scene development which does not effectively provide the end user the experience and information required, scenes are limited to patients who are going to the hospital. Using a limited prototype is a means of storyboarding and rapid development that can be further built upon using an iterative method (Moreno-Ger et al., 2012).

The general requirement for all two scenes is to allow the user to explore the travel of patients from the sending to the receiving institution. A camera the user can control and move about the scene will allow the user to view patients visualized moving from the sending to the receiving institution. With the ability for the end user to move freely about the scene will help to immerse the user in the scene.

To start the patient from the sending institution, spawning code is developed so that the patient and arrival mode can be randomized to the required percentage and the frequency. Other patient attributes requiring a probability or other based distribution such as age, gender and method of arrival can also be implemented during this spawning process. The spawning of a patient could be customized for each sending institution.

4. Patient Flow Visualisation Demonstration Instantiation

For the purposes of the demonstration, the scenes visualize patient flow to the hospital (i.e., travelling from a starting location to a central hospital). The hospital scenario for the case study is based on a typical Group B Ontario Canada hospital having no fewer than 100 beds (Ontario Ministry of Health and Ministry of Long-Term Care, 2001). There are 52 hospitals that comprise of Group B out of a total of 151 public not-for-profit hospitals in Ontario and with the total hospitals serving over 15.1 million ED visits between 2019 and 2020 (Canadian Institute for Health Information, 2022) For this research a typical regional Ontario hospital with 400 beds and 90,000 annual ED visits will be used. The average time spent in the ED at a regional hospital for complex patients requiring more diagnoses and treatments was six hours and 9 out 10 complex patients spending 12.9 hours in ED (MOHLTC, n.d.). For minor or uncomplicated patients average time spent in ED was 1.9 hours and total time spent in ED (9 out of

10 patients) was 3.2 hours (MOHLTC, n.d.). By using a regional hospital as a test scenario allows for VR SG VE to demonstrate the potential benefits on a moderate size regional hospital.

4.1 Dataset

A typical regional hospital will have an extensive electronic data set contained in an EMR with the necessary patient movement information, a simulated dataset was used for this paper to demonstrate the effectiveness of visualizing patient flow for making decisions. Patient gender and mode of transportation (either by ambulance or other) was randomly generated to allow a simulation of patient traveling from the sending hospital to the regional hospital. Using randomly generated patients, the user can then focus on the immersion, usability and playability of each scene.

4.2 Scene Development

The first scene is a simplified rendering of sending hospitals to the regional hospital (See Figure 1). The simplified scene uses a cylinder object for the patient and color codes the gender and arrival mode. The scene does use building assets specifically hospitals to represent the sending institution and the regional hospital the receiving institution. The user can move about the scene and zoom in or out or pan around to observe the patient movement with the camera.

The second scene is semi-realistic which includes terrain, cars, ambulances and building assets (See Fig 2.). The building assets are more specific such that hospitals and long-term care facilities are different. The user can also move about the scene to observe the movement of the patient from the sending institution to the regional hospital. A white ambulance is shown which the color code for a male arriving by ambulance and a green ambulance would be a female. A blue car would be male, and a red car would be female for patients not arriving by ambulance.

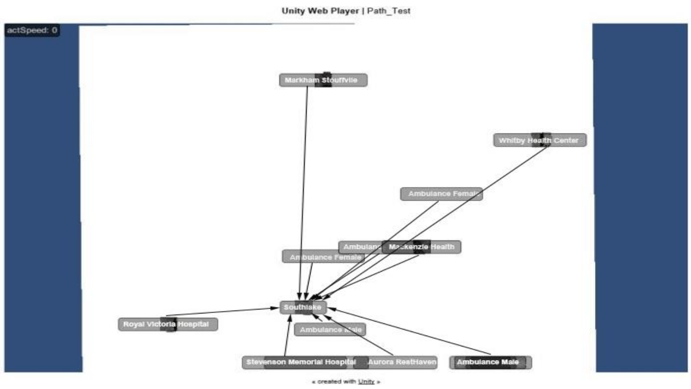

Figure 1: Simplified example developed in Unity

Figure 2: Semi-realistic example developed in Unity

To help the user identify the patient and where they came from as they move from the sending institution, the patient object was tagged with a text that floated along with patient as they moved to the regional hospital. Once the patient object arrived the patient object would be destroyed by the regional hospital object to minimize memory usage.

The proposed gender split was 50 percent male and 50 percent female with 30% arriving via ambulance. The sending institution comprised of long-term care facilities (LTC) and other hospitals. Closer LTC to the regional hospital had a higher percentage of patients sent to the regional hospital. Hospitals that were closer also had higher percentage of patients sent to the regional hospital but not as high as close LTC. The data was estimated to provide sufficient numbers that will allow the user to gauge the effectiveness of the immersion and usability.

5.0 Future Work

While this paper detailed using a VR SG to show patient flow to the ED the future work will include extending the VR SG to include the hospital as a whole system of the complete patient journey from admission to discharge and their final destination (Brailsford et al., 2019;). Developing a VE using VR and SG will require the VE to be sufficiently immersive to give the user a sense of presence (A. Sutcliffe & Gault, 2004). To ensure sufficient immersion and ultimately a sense of presence the VE will need to be sufficiently immersive along with playable as determined by the user. Playability is key in SG and require a more holistic integration of components and determination whether the user experience is positive or not (Olsen et al., 2011). The SG must be developed to ensure the SG is engaging, usable, playable and delivers educational value to the user (Olsen et al., 2011). The following are additional considerations for Future Work which will be detailed in a subsequent research and paper.

5.1 Big Data

As part of the extending to a whole system, a year's data set of ADT, DAD and NACRS will provide an even more effective view of patient flow that, when visualized, will enable the user to better extrapolate to the real world to find patterns, trends and complex workflow relationships more effectively (Drechsler & Soeken, 2013). Unity has been shown to handle large data sets that users can interact with in a VE (Donalek et al., 2014).

5.2 Virtual Reality

A realistic portrayal of a regional hospital catchment area including roads and buildings could be developed. The roads for the catchment area have been captured by using Open Street Maps (Figure 3 https://www.openstreetmap.org/#map=9/43.7522/-78.6676) which can produce an export that EasyRoads3d, a road development asset available to Unity, can import into Unity creating a realistic view of the road networks around regional hospital. The realistic scene could use high fidelity 3D objects and assets to provide a more immersive environment for the user. Additionally, the technology that is used to render the VR should allow visualization exploration based on how the end user will use the VE in a hospital setting (see Figure 4). A future study would look at what is the most effective visualization rendered to encapsulate a whole system patient flow in a VE.

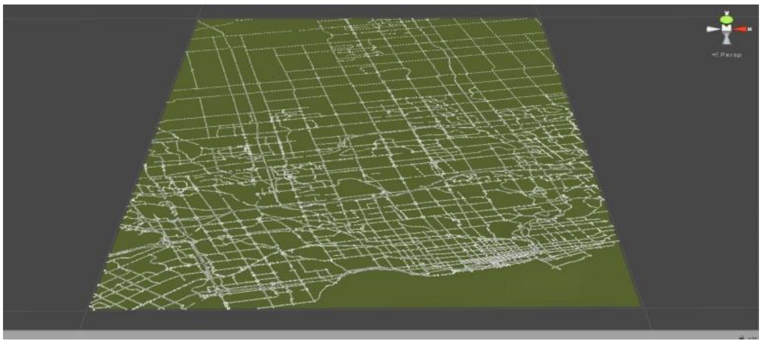

Figure 3: Open Street Map rendered in Unity

5.2 Usability and Playability Testing

The future VE will be designed and developed by engaging a hospital subject matter expert (SME) who is familiar with patient flow. The designed and developed VE will be tested against the 12 Heuristics proposed by Sutcliffe et. al (2004) that will evaluate usability and presence of the VE (A. Sutcliffe & Gault, 2004). The 12 Heuristics consist of natural engagement, compatibility with the user's task and domain, natural expression of action, close coordination of action and representation, realistic feedback, faithful viewpoints, navigation and orientation support, clear entry and exit points, consistent departures; support for learning, clear turn-taking and sense of presence (A. Sutcliffe & Gault, 2004). To test the usability of the SG component of the VE, the Serious Game Usability Evaluator (SeGUE) will be used, which evaluates 6 system elements and 11 user dimension criteria (Moreno-Ger et al., 2012). Additionally, during the design and development along with the usability testing, the playability of VE will also be evaluated using the 15 Playability Heuristics as described by Aker (2019)(Aker et al., 2019).

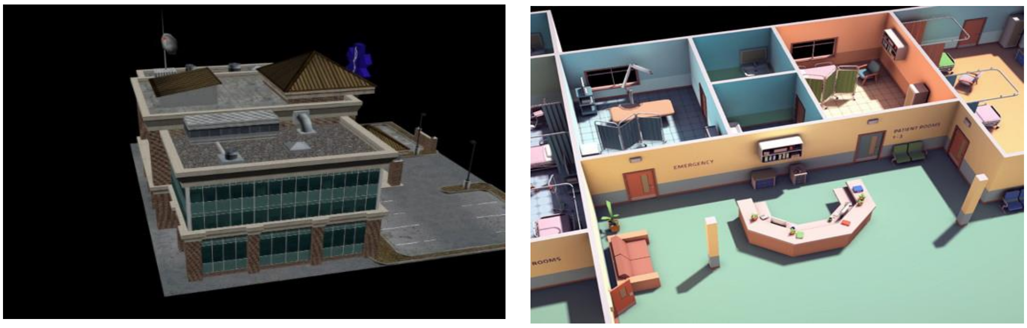

Figure 4: Examples of Unity hospital and patient ward assets

Once the developed VE is deemed to be usable and playable by the SME that collaborated on the design and development a more extensive usability study will be conducted to ensure the VE is usable and playable by a wider user group. The typical rule of thumb usability test is using a sample size of 5 to 8 users and is deemed to uncover 80% of the usability issues (NIELSEN, 2000; Virzi, 1992). The underlying assumption are the 5 to 8 users are experienced but in fact the participants experience in the usability test may vary (Faulkner, 2003). The future work will conduct a 4-user usability test to determine the number of usability issues one user can find. Based on the number of usability issues uncovered by one user a sufficiently powered sample size can be determined (Faulkner, 2003). By conducting a sufficiently powered sample the usability of the VE can be determined to ensure that the VE is usable and playable to view patient flow as a whole system in a hospital (Faulkner, 2003).

6. Conclusion

This paper has presented a method for VR simulation using SG to create a VE. We demonstrated how patient flow can be visualized using SG and VR through an emergency department case study. Using VR and SG has an opportunity to provide a new and novel method of visualizing complex healthcare operational data that would provide a user-friendly environment for healthcare administrators or operational users. This research used a limited development in Unity to test the applicability and depth of immersion, usability and playability required by end user and will ensure resources are efficiently used. The expectation is that one scene or a derivative of will be selected to develop a comprehensive scene that depicts patient flow from beginning to end and detail the bottlenecks, "bed blockers" and inefficiencies. Once the bottlenecks and inefficiencies are uncovered healthcare administration and operational personnel can address the bottlenecks and inefficiencies to improve the patient flow through and out of the hospital and reduce associated wait-times. The end goal will be to provide the patient with better and improved efficiency of care provision by examining the patient flow as a whole system. The work detailed in this paper will be the basis for the future development of a whole system developed VE that will be sufficiently immersive, usable and playable.

References

Adamo-Villani, N., Haley-Hermiz, T., & Cutler, R. (2013). Using a serious game approach to teach "operator precedence" to introductory programming students. *Proceedings of the International Conference on Information Visualisation*, 523–526. https://doi.org/10.1109/IV.2013.70

Affleck, A., Parks, P., Drummond, A. J., Rowe, B. H., & Ovens, H. J. (2012). Emergency Department overcrowding and access block. *Canadian Journal of Emergency Medicine*, *14*(2), 106–112. https://doi.org/10.2310/8000.CAEPPS

Aker, Ç., Rızvanoğlu, K., & Bostan, B. (2019). Methodological review of playability heuristics. *Contemporary Topics in Computer Graphics and Games*, *December*, 81–117.

Bowman, D. a, Mcmahan, R. P., & Tech, V. (2007). Virtual Reality: How Much Immersion Is Enough? (Cover story). *Computer*, *40*(7), 36–43. http://ezlibproxy.unisa.edu.au/login?url=http://search.ebscohost.com/login.aspx?direct=true&db=aph&AN=25758828&site=ehost-live

Buttigieg, S. C., Pace, A., & Rathert, C. (2017). Hospital performance dashboards: a literature review. *Journal of Health, Organisation and Management*, *31*(3), 385–406. https://doi.org/10.1108/JHOM-04-2017-0088

Canadian Institute for Health Information. (2022, May 26). *NACRS emergency department visits and lengths of stay*.

Chen, M., Mao, S., & Liu, Y. (2014). Big data: A survey. *Mobile Networks and Applications*, *19*(2), 171–209. https://doi.org/10.1007/s11036-013-0489-0

CIHI, & NACRS. (2014). *Emergency Department Highlights in 2013–2014*. https://secure.cihi.ca/free_products/NACRS_ED_QuickStats_Infosheet_2013-14_ENweb.pdf

Clissold, A., Filar, J., Mackay, M., Qin, S., & Ward, D. (2015). Simulating hospital patient flow for insight and improvement. *Proceedings of the 8th Australasian Workshop on Health Informatics and Knowledge Management (HIKM 2015)*, *January*, 27–30.

Djorgovski, S. G. (2012). Novel Approaches to Data Visualization Opening Remarks Effective visualization is the bridge between quantitative information and human intuition. *MSR EScience 2012 Workshop*.

Donalek, C., Djorgovski, S. G., Cioc, A., Wang, A., Zhang, J., Lawler, E., Yeh, S., Mahabal, A., Graham, M., Drake, A., Davidoff, S., Norris, J. S., & Longo, G. (2014). Immersive and Collaborative Data Visualization Using Virtual Reality Platforms. *IEEE International Conference on Big Data*, 609–614.

Drechsler, R., & Soeken, M. (2013). Hardware-Software Co-Visualization: Developing systems in the holodeck. *Proceedings of the 2013 IEEE 16th International Symposium on Design and Diagnostics of Electronic Circuits and Systems, DDECS 2013*, 1–4. https://doi.org/10.1109/DDECS.2013.6549775

Drummond, A. J. (2002). No room at the inn : overcrowding in Ontario ' s emergency departments. *Canadian Journal Of Emergency Medicine*, *4*(2), 91–97.

Esensoy, A. V., & Carter, M. W. (2018). High-fidelity whole-system patient flow modeling to assess health care transformation policies. *European Journal of Operational Research*, *266*(1), 221–237. https://doi.org/10.1016/j.ejor.2017.09.019

Faulkner, L. (2003). Beyond the five-user assumption: benefits of increased sample sizes in usability testing. *Behavior Research Methods, Instruments, & Computers : A Journal of the Psychonomic Society, Inc*, *35*(3), 379–383. https://doi.org/10.3758/BF03195514

Feldman, B., Martin, E. M., & Skotnes, T. (2012). Big Data in Healthcare - Hype and Hope. *Dr.Bonnie 360 Degree (Business Development for Digital Health)*, *2013*(1), 122–125. http://www.riss.kr/link?id=A99883549

Fosso Wamba, S., Akter, S., Edwards, A., Chopin, G., & Gnanzou, D. (2015). How "big data" can make big impact: Findings from a systematic review and a longitudinal case study. *International Journal of Production Economics*, *165*, 234–246. https://doi.org/10.1016/j.ijpe.2014.12.031

Gantz, J., & Reinsel, D. (2011). Extracting Value from Chaos State of the Universe: An Executive Summary. In *IDC iView* (Issue June). https://doi.org/10.1007/s10916-016-0565-7

Graafland, M., Schraagen, J. M., & Schijven, M. P. (2012). Systematic review of serious games for medical education and surgical skills training. *British Journal of Surgery*, *99*, 1322–1330. https://doi.org/10.1002/bjs.8819

Hamrock, E., Paige, K., Parks, J., Scheulen, J., & Levin, S. (2014). Relieving emergency department crowding: Simulating the effects of improving patient flow over time. *Journal of Hospital Administration*, *4*(1), 43–47. https://doi.org/10.5430/jha.v4n1p43

Handel, D. a., Wears, R. L., Nathanson, L. a., & Pines, J. M. (2011). Using information technology to improve the quality and safety of emergency care. *Academic Emergency Medicine*, *18*(6), 45–51. https://doi.org/10.1111/j.1553-2712.2011.01070.x

Hashem, I. A. T., Yaqoob, I., Anuar, N. B., Mokhtar, S., Gani, A., & Ullah Khan, S. (2015). The rise of "big data" on cloud computing: Review and open research issues. *Information Systems*, *47*, 98–115. https://doi.org/10.1016/j.is.2014.07.006

Henderson, S., & Mason, A. (2000). BartSim: A tool for Analysing and Improving Ambulance Performance in Auckland, New Zealand. *New Zealand, Wellington, New*. http://www3.esc.auckland.ac.nz/people/staff/amas008/Papers/ORSNZ2000BartSim/BartSim.pdf

Laney, D. (2001). META Delta. In *Application Delivery Strategies* (Vol. 949, Issue February 2001). https://doi.org/10.1016/j.infsof.2008.09.005

McGregor, C. (2018). Using Constructive Research to Structure the Path to Transdisciplinary Innovation and Its Application for Precision Public Health with Big Data Analytics. *Technology Innovation Management Review*, *8*(8), 7–15. https://doi.org/10.22215/timreview/1174

Mohiuddin, S., Busby, J., Savović, J., Richards, A., Northstone, K., Hollingworth, W., Donovan, J. L., & Vasilakis, C. (2017). Patient flow within UK emergency departments: A systematic review of the use of computer simulation modelling methods. *BMJ Open*, *7*(5). https://doi.org/10.1136/bmjopen-2016-015007

MOHLTC. (n.d.). *Southlake Regional Provincal Emergency Department Wait Times*. Retrieved April 22, 2015, from http://www.ontariowaittimes.com/er/en/Data.aspx?LHIN=0&city=&pc=&dist=0&hosptID=4001&str=S&view=0&period=0&expand=0

Moreno-Ger, P., Torrente, J., Hsieh, Y. G., & Lester, W. T. (2012). Usability testing for serious games: Making informed design decisions with user data. *Advances in Human-Computer Interaction*, *2012*. https://doi.org/10.1155/2012/369637

NIELSEN, J. (2000). *Why You Only Need to Test with 5 Users*. http://www.nngroup.com/articles/why-you-only-need-to-test-with-5-users/

OECD. (2013). *Health at a Glance 2013, OECD Indicators*. https://doi.org/10.1787/health_glance-2013-en

Olsen, T., Procci, K., & Bowers, C. (2011). Serious games usability testing: How to ensure proper usability, playability, and effectiveness. *Lecture Notes in Computer Science (Including Subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics), 6770 LNCS*(PART 2), 625–634. https://doi.org/10.1007/978-3-642-21708-1_70

Ontario Ministry of Health and Ministry of Long-Term Care. (2001). *Public Hospitals Act / Loi sur les hôpitaux publics*. Regulation 964 - Amended to O. Reg. 321/01 Classification Of Hospitals. https://www.health.gov.on.ca/en/common/system/services/hosp/hospcode.aspx

Organisation for Economic Cooperation and Development (OECD). (2021, November 9). *Occupancy rate of curative (acute) care beds, 2009 and 2019 (or nearest year)*. Health at a Glance 2021: OECD Indicators. https://doi.org/https://doi.org/10.1787/9886c0af-en

Organization for Economic Co-Operation and Development. (2019). *OECD.Stat Health Care Resources: Hospital beds by sector*. https://stats.oecd.org/

Sarathy, S., Shujaee, K., & Cannon, K. (2000). Visualization of large complex datasets using virtual reality. *Proceedings International Conference on Information Technology: Coding and Computing (Cat. No.PR00540)*, 1–5. https://doi.org/10.1109/ITCC.2000.844280

Sinclair, D. (2007). Emergency department overcrowding - Implications for paediatric emergency medicine. *Paediatrics and Child Health*, *12*(6), 491–494.

Slater, M. (2003). A Note on Presence Terminology. *Emotion*, *3*, 1–5.

Sutcliffe, A., & Gault, B. (2004). Heuristic evaluation of virtual reality applications. *Interacting with Computers*, *16*(4), 831–849. https://doi.org/10.1016/j.intcom.2004.05.001

Tsoy, D., Sneath, P., Rempel, J., Huang, S., Bodnariuc, N., Mercuri, M., Pardhan, A., & Chan, T. M. (2019). Creating GridlockED: A Serious Game for Teaching about Multipatient Environments. *Academic Medicine*, *94*(1), 66–70. https://doi.org/10.1097/ACM.0000000000002340

Virzi, R. A. (1992). Refining the test phase of usability evaluation: How many subjects is enough? *Human Factors*, *34*(4), 457–468. https://doi.org/10.1177/001872089203400407

Wang, T. D., Plaisant, C., Quinn, A. J., Stanchak, R., & Murphy, S. (2008). Aligning Temporal Data by Sentinel Events : Discovering Patterns in Electronic Health Records. *CHI 2008 Proceedings · Health and Wellness*, 457–466. https://doi.org/10.1145/1357054.1357129

Zyda, M. (2005). From visual simulation to virtual reality to games. *Computer*, *38*(9), 25–32. https://doi.org/10.1109/MC.2005.297