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Quantitative metrics for evaluating the phased roll-out of clinical information systems

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**A R T I C L E   I N F O**

**Keywords:**
Clinical information systems
Algorithms
Information systems
Implementation

**A B S T R A C T**

**Objectives:** We introduce a novel quantitative approach for evaluating the order of roll-out during phased introduction of clinical information systems. Such roll-outs are associated with unavoidable risk due to patients transferring between clinical areas using both the old and new systems.

**Methods:** We proposed a simple graphical model of patient flow through a hospital. Using a simple instance of the model, we showed how a roll-out order can be generated by minimising the flow of patients from the new system to the old system.

**Results:** The model was applied to admission and discharge data acquired from 37,080 patient journeys at the Churchill Hospital, Oxford between April 2013 and April 2014. The resulting order was evaluated empirically and produced acceptable orders.

**Discussion:** The development of data-driven approaches to clinical Information system roll-out provides insights that may not necessarily be ascertained through clinical judgment alone. Such methods could make a significant contribution to the smooth running of an organisation during the roll-out of a potentially disruptive technology.

**Conclusion:** Unlike previous approaches, which are based on clinical opinion, the approach described here quantitatively assesses the appropriateness of competing roll-out strategies. The data-driven approach was shown to produce strategies that matched clinical intuition and provides a flexible framework that may be used to plan and monitor Clinical Information System roll-out.

1. Introduction

The implementation of hospital Clinical Information Systems (CISs) is known to be complex. Poor implementation has previously led to delays in full functionality, and in the worst cases, systems remaining partially deployed for long periods \cite{1–3}. In many instances, poor performance following the introduction of a CIS may be attributed to the system not functioning as intended. For instance, Darbyshire reported how one such CIS was considered unsuitable by clinical end users \cite{4}. In contrast, Huerta et al. showed that the effect of a CIS on hospital productivity depended on the rollout strategy, which suggests an effect due to the implementation process itself \cite{5}.

One key decision during CIS implementation is the roll-out strategy used to determine how the system is introduced into each clinical area. CISs can be rolled-out according to one of two broad approaches. In a big-bang approach, the whole system is adopted over a very short period of time for a whole hospital site. Alternatively, in a phased approach, subsections of the hospital are moved to the new system over an extended period of time. The phased approach may also refer to the gradual release of system functionality, such that users are not immediately exposed to a system’s full capabilities.

Big-bang implementations have previously been recommended for stable systems that do not contain critical functionality \cite{6}. In practice, technical constraints mean that a big-bang approach is often appealing \cite{7}. For instance, in the case of Computerised Physician Order Entry (or e-Prescribing) systems, simultaneous deployment in clinical areas and pharmacy, is necessary to ensure that drug orders can be completed using the new system \cite{8}. Other practical considerations such as financial and time constraints may also influence the implementation approach (for example, if required human resource is only available for a short duration). The drawback of the big-bang is that it exposes an organisation to a large degree of short-term risk. A successful big-bang must ensure that all IT infrastructure and organisational processes, including staff training and down-time procedures, are in place ahead of roll-out \cite{9}. Phased roll-out limits risks by confining initial deployment to a small area. This allows early validation of the system and also
reduces the initial resource required [9,10]. After the initial validation,
the phased approach allows for mid-course corrections that are not
possible in a big-bang methodology [11]. Furthermore, a phased roll-
out offers opportunities to study the effect of a new system using a
stepped-wedge approach [12,13]. This methodology monitors an in-
tervention over time, allowing the effect of temporal confounders to be
identified.

Phased roll-outs introduce their own problems, including an ex-
tended transition period between the existing and new system. During
this transition phase, uncertainty in clinical process may lead to dup-
plication of documentation on both the old and new systems, or worse,
omission of data from either system [14,15]. For this reason, current UK
guidelines on the implementation of e-Prescribing systems recommend
rapid phased rollouts, colloquially described as ‘rolling thunder’ [16].

The order in which clinical areas, or groups of areas, are introduced
to the new system is a key design decision for phased roll-out. The order
of the roll-out is determined by multiple factors. Technical factors in-
clude the system’s usability which may be influenced by more wide-
spread IT infrastructure failings such as poor Wi-Fi coverage, as well as
system performance and financial cost. Social considerations include
how well staff engage with a new system. For example, the reticence of
clinical staff to engage with new systems has been well-documented as
a key problem [17,18].

Organisational factors include effective change management, pro-
vision of clear leadership (clinical champions), and successful evalua-
tion of the system [19,20]. Finally, patient safety must be considered.
One possible approach is to minimise the number of patient episodes
documented using both old and new systems.

In practice, the order of clinical areas in a phased roll-out is usually
chosen in an ad-hoc manner. In the best cases, CIS roll-out strategy is
informed by qualitative information such as on-site interviews to assess
human resources, emotional ability to support an CIS, and office dy-
namics [16,21], whereas often there is no documented strategy.

We address the issue of roll-out order in phased implementation
using a graphical framework. The framework explicitly models patient
transit between clinical areas using the old and new systems. In doing
so, it directly quantifies factors related to both patient safety and
clinical workflow. Whilst consideration of patient transits does not ac-
count for Organisational or Technical factors, the proposed framework
may be adapted to include such factors. We show a simple example of
this framework applied to the rollout of an electronic vital sign ob-
servation system. The example shows how different ordering strategies
can be compared to identify areas at greater risk of patient information
being stored on multiple systems, which may complicate clinical care.

2. Methods

2.1. Model

We model a hospital as a directed graph in which clinical areas are
nodes. Each area, , has a state, , indicating whether it is on the old
(s = 0) or new (s = 1) system. Clinical factors that may impact the
effectiveness of a CIS rollout are modelled in two ways. First, the
number of patients transferring between two areas per unit time are
modelled as weighted edges. The set of transfers into area is denoted
by , and the set of transfers out are denoted . Other clinical factors
associated with area are represented by a feature vector, . In
practice, elements of might include ward acuity (on a scale of 0–3)
[22], staff to patient ratio. The general model is depicted in Fig. 1.

The impact of an area changing state from 0 to 1 is evaluated
through a cost function,

\[ \delta(w) = \delta(I_w, O_w, V_w) \]

The form of the function is set on a case-by-case basis and determined by the relative importance
of each factor. The need to explicitly choose a function, a priori, is
comparable to other modelling techniques such as Gaussian Process
regression [23].

Having developed a model and cost function, a greedy algorithm
(Algorithm 1) can be used to determine a roll-out order [24]. In a
greedy algorithm, the ordering is constructed one area at a time. Each
area is chosen by selecting the one that minimises the cost function
given the order that has been constructed so far. The chosen area is then
appended to the current order.

Algorithm 1. Clinical area order algorithm

Assuming is the set of all clinical areas, is a list of ordered clinical areas,
and is the cost function

\[ \text{while } W \neq \emptyset \]
\[ \text{find } w \in W \text{ that minimizes } \delta(w) \]
\[ \text{let } W := \text{delete}(w, W) \]
\[ \text{let } p := \text{append}(w, p) \]

2.2. Model instance

One instantiation of the model is now described for the problem of
phased roll-out between paper and electronic (e-Obs) systems for re-
cording vital signs. Fig. 2 shows a simple model of a hospital containing
6 clinical areas, labelled A to F. Patients arrive at the hospital from the
pre-hospital population, , and leave to the post-hospital population, .

The number of patients transferring between wards per unit time are
denoted by the edge weights, , for example, 3 patients/time transfer
between A and C.

To generate a rollout order, the cost function, , must first be
defined. To define the cost function we consider that, during a phased
rollout, patients may transit between the two systems in the following ways:

1. paper → paper
2. paper → e-Obs
3. e-Obs → paper
4. e-Obs → e-Obs

Transition 1 represents current practice where a paper based system
is ubiquitous and is considered to be of acceptable clinical risk. Transition 2 replaces patient movements in which the receiving and
sending areas are using e-Obs. We consider this to be a more acceptable
clinical risk, since this is the desired transition after roll-out. Transitions
2 and 3 pose greater clinical risk, since these only occur during the
phased roll-out. In both of these situations, data must be stored on two
separate systems. This may result in situations where clinical staff are
unaware to quickly synthesize the full patient record. However, transition
2, from paper to e-Obs, is unavoidable in a phased roll-out.

Therefore, the simplest usable cost function considers only the
number of patients with an electronic → paper transition. No other
features are included, so is not used in this instance. The number of
e-Obs → paper transitions is simply the sum of the subset of for which
adjacent areas have a state

\[ \delta(w) = \sum_{i \in W} q_i \times r_i \]

In the event that two or more areas have the same value of , we
may consider the net number of paper → e-Obs transition as a tie-
breaker.

A rollout order can now be generated by applying Algorithm 1 using
this cost function. The result of two steps of the algorithm is presented
pictorially in Fig. 2. In the first step, all clinical areas are considered and
their cost functions are calculated. The cost and tiebreaker are shown as
the pair (, tiebreak(w)) in the first column of Table 1. Initially, area
is activated, since and the tie break is smaller than that of
area (for which ). In the second step, is no longer

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considered, since $E$ has been deleted from the remaining areas, $W$. The order selected by the algorithm is: $E \rightarrow F \rightarrow C \rightarrow D \rightarrow B \rightarrow A$. In this simple example, the algorithm produces a roll-out order in which no patients ever switch from e-Obs $\rightarrow$ paper.

2.3. Extended model instance

A more realistic cost function should consider the effect of other external influences such as clinical area specialty. In practice, areas with similar specialties are grouped into directorates that often share common staff. Migrating areas within a directorate in close succession may simplify staff training and minimise the amount of time that staff have to retain knowledge of both systems.

With this in consideration, transitions between areas in the same directorate might be weighted differently to those outside the directorate. The cost function can then be modified:

$$\delta(w) = d(v_i) \sum_{i \in W} o_{i \rightarrow w}$$

$$d(v_i) = \begin{cases} x & v_i = v_w \\ 1 & \text{otherwise} \end{cases}$$

The constant $x$ is a parameter that weights the importance of intra-directorate transitions. The Matlab code for both of the basic and extended model instances is available from [www.robots.ox.ac.uk/~wong](http://www.robots.ox.ac.uk/~wong).

2.4. Data

Data were acquired from the Churchill Hospital, Oxford, UK (Oxford University Hospitals Foundation NHS Trust), which had been chosen as the initial roll-out site for a new e-Obs system [25]. The hospital had 37,080 direct admissions between April 2013 and April 2014. For each admission, the Trust informatics department queried the Electronic Patient Record to obtain the clinical areas in which patients were admitted during their stay, in chronological order.
The data were processed as an adjacency matrix that fully defines the graph model outlined previously. The organisational structure of the hospital, containing information about each of the clinical directorates, was ascertained through publicly-available documentation, and is shown in Table 2.

This research was approved as a service evaluation for Oxford University Hospitals Foundation Trust (Datix: 2920). As no patient identifiable data was analysed, the study did not require review by the National Research Ethic Service.

### 3. Results

Admissions data were used to generate the graphical model, showing the clinical areas and annual patient transitions between April 2013 and April 2014 (Fig. 3). For clarity, only edges with weights of 30 or greater are shown and nodes that represent day case units have been removed.

The visualisation highlights clinically significant features unique to this data set. By inspection, we note that the graph has three primary clusters of inter-connected clinical areas highlighted in red, blue and green. These clusters relate to clinical areas with similar specialties. Nodes coloured in red relate to areas that specialise in respiratory problems, nodes in blue relate to cancer clinical areas, and green nodes denote surgical clinical areas. The remaining area, Endocrinology, was coded as a standard clinical area, but acts as a day unit that works independently from the rest of the hospital.

Fig. 3 shows that there are relatively few complex patient pathways. Of the hospital clinical areas, Day Surgery Unit and ICU have the most outgoing edges, and thus the most transitions, to other clinical areas. One would therefore intuitively expect both clinical areas to be ordered last by the greedy algorithm; Table 3 confirms this to be true. One

<table>
<thead>
<tr>
<th>Directorate 1</th>
<th>Directorate 2</th>
<th>Directorate 3</th>
<th>Directorate 4</th>
<th>Directorate 5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resp X-ray</td>
<td>Head and Neck</td>
<td>Recovery</td>
<td>Renal</td>
<td>Upper GI</td>
</tr>
<tr>
<td>Endocrinology</td>
<td>Palliative Care</td>
<td>ICU</td>
<td>Urology</td>
<td>Lower GI</td>
</tr>
<tr>
<td>Respiratory</td>
<td>Haematology</td>
<td>Day Surgery</td>
<td>Transplant</td>
<td></td>
</tr>
<tr>
<td>Resp Day Case</td>
<td>Haem Day Case</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Infectious Disease</td>
<td>Oncology</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Oncology SS</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Endocrinology</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Dermatology</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Table 2**

Clinical directorates and their constituent clinical areas.

---

Fig. 3. Graph showing patient transfers between clinical areas at the Churchill Hospital, Oxford. For clarity, only inter-clinical area transfers of more than 30/year are shown, and day-case units for which there were very few inter-clinical area transfers have also been excluded.
Table 3
Recommended clinical area orders derived from the Model Instance and Extended Model Instance.

<table>
<thead>
<tr>
<th>Order</th>
<th>Without Directorate</th>
<th>With Directorate</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Head and Neck</td>
<td>Head and Neck</td>
</tr>
<tr>
<td>2</td>
<td>Palliative Care</td>
<td>Resp X-ray</td>
</tr>
<tr>
<td>3</td>
<td>Renal</td>
<td>Endocrinology</td>
</tr>
<tr>
<td>4</td>
<td>Resp X-ray</td>
<td>Palliative Care</td>
</tr>
<tr>
<td>5</td>
<td>Endocrinology</td>
<td>Haem Day Case</td>
</tr>
<tr>
<td>6</td>
<td>Recovery</td>
<td>Renal</td>
</tr>
<tr>
<td>7</td>
<td>Urology</td>
<td>Oncology</td>
</tr>
<tr>
<td>8</td>
<td>Lower GI</td>
<td>Resp Day Case</td>
</tr>
<tr>
<td>9</td>
<td>Respiratory</td>
<td>Respiratory</td>
</tr>
<tr>
<td>10</td>
<td>Resp Day Case</td>
<td>Urology</td>
</tr>
<tr>
<td>11</td>
<td>Infectious Disease</td>
<td>Haematology</td>
</tr>
<tr>
<td>12</td>
<td>Haematology</td>
<td>Infectious Disease</td>
</tr>
<tr>
<td>13</td>
<td>Haem Day Case</td>
<td>Recovery</td>
</tr>
<tr>
<td>14</td>
<td>Oncology</td>
<td>Lower GI</td>
</tr>
<tr>
<td>15</td>
<td>Colorectal</td>
<td>Oncology SS</td>
</tr>
<tr>
<td>16</td>
<td>Oncology SS</td>
<td>Colorectal</td>
</tr>
<tr>
<td>17</td>
<td>Upper GI</td>
<td>Upper GI</td>
</tr>
<tr>
<td>18</td>
<td>Transplant</td>
<td>Transplant</td>
</tr>
<tr>
<td>19</td>
<td>ICU</td>
<td>ICU</td>
</tr>
<tr>
<td>20</td>
<td>Day Surgery</td>
<td>Day Surgery</td>
</tr>
</tbody>
</table>

would also expect clinical areas from which patients are commonly discharged from the hospital to be ordered near the start. These include Endocrinology, Palliative Care, and Head and Neck, which each have only one outgoing edge. Given the typical type of patient in the clinical areas, one may have expected Palliative Care at the start of the ordering (in practice, of course, vital signs would not be required). However, the algorithm lists Head and Neck to be rolled out initially. This is likely due to incomplete data, as the Head and Neck area became clinically active part way through the data collection period.

To compare the effectiveness of two competing roll-out strategies, we use the number of e-Obs \( \rightarrow \) paper transitions as a cost function. The total cost of the roll-out is then the cumulative number of transitions after rollout. By calculating the cost after the activation of each clinical area, we can also highlight areas that are likely to be more problematic. Fig. 4 shows the estimated cost (cumulative number of electronic to paper transitions) under two roll-out strategies: the standard and directorate-adjusted algorithms.

4. Discussion

The results presented here show how a model of patient flow between clinical areas can be used to guide decision making during CIS phased roll-out. We presented a cost function that quantitatively evaluates the clinical impact of switching between CIS systems. The cost function, coupled with a greedy algorithm, allowed us to generate a sensible clinical area order using real data.

The greedy algorithm was chosen to demonstrate how the model could be simply interpreted in a useful manner. A significant benefit of the greedy algorithm approach is that it is able to cope with practical numbers of clinical areas. Given N clinical areas, the time for the algorithm to complete is proportional to \( N^3 \) (i.e. \( O(N^3) \)) if each area is connected to every other area. In reality, most clinical areas are more sparsely connected, which means that the order is \( O(N^2) \) in practice. If a naive approach to calculating a clinical area order were used instead, one would consider all permutations of orderings leading to an intractable solution requiring \( O(N!) \) calculations.

In an ideal situation, the combination of optimal sub-solutions would lead to an optimal solution. When this is the case, alternative approaches such as dynamic programming may be employed which leads to a correct and efficient implementation. However, we have no assurance that the cost functions considered here lead to this principle of optimality, and so we must resort to a greedy approach. Our approach is therefore heuristic and cannot guarantee that the optimal result ensues.

We further demonstrated, using clinical directorates as an example, how the cost function can incorporate additional factors. Table 3 showed that the inclusion of clinical directorates had a limited effect on the proposed order. Highly connected clinical areas, such as Day Surgery Unit and Intensive Care Unit, which were ordered last in the standard algorithm remained last in the directorate-adjusted algorithm. Similarly, many of the initial clinical areas had a similar order. The reason for the similarity between the two clinical area orders is that the number of intra-directorate patient transfers was small in comparison to the inter-directorate transfers.

When there were differences in order, the cumulative number of e-Obs \( \rightarrow \) paper transitions (Fig. 4) indicated whether the differences were important. There were more transitions in the directorate model than in the basic model, as the directorate model attempts to optimise competing goals (transitions and ward grouping). Visual inspection of the directorate-adjusted clinical area order showed large increases in cost for areas 5, 8 and 15. These indicate clinical areas for which there are a high numbers of e-Obs \( \rightarrow \) paper transitions and may have greater practical difficulties during roll-out.

The comparison of cumulative cost in Fig. 4 allowed us to identify, prior to roll-out, individual clinical areas in the roll-out order that may cause extra difficulties due to high numbers of e-Obs \( \rightarrow \) paper transitions. This analysis shows how a CIS implementation strategy may be

![Fig. 4. The cumulative number of patients (annually) with e-Obs \( \rightarrow \) paper transitions (cost) by roll-out step for the without (grey) and with (black) directorate clinical area orderings.](image)
analysed and refined prior to live roll-out. The method may also be applied on real-time data to monitor progress of deployment. In the event of an unexpectedly high number of transitions, the approach here would allow a change of strategy mid-deployment as espoused by Catwell [26].

Whilst we have only considered the phased roll-out of individual clinical areas, the proposed approach may be extended for a ‘rolling-thunder’ roll-out. Under this scenario, groups of clinical areas to be rolled-out simultaneously would be modelled as a single node. Alternative groupings may be tested, and evaluated using the cumulative cost.

The approach of modelling flows between wards may also be used for other clinical information systems. For instance, modelling patient flows would be appropriate for blood/patient tagging, whereas one may wish to model clinician location for a change in hospital communication system (e.g., bleep to phone). For a general CIS, it may be that other clinical factors, such as the level of staff training, the ward acuity or type (medical or surgical), or staff-to-patient ratio may be more important than patient transfers. In such scenarios, the additional factors may be included in the variable, $V_w$. A corresponding cost function would then be required to weight each factor. The choice of cost function would rely on clinical judgment. However, unlike current approaches, any clinical assumptions would be modelled explicitly.

5. Conclusion

In this paper, we developed a framework for quantitatively assessing the phased rollout of CISs. The approach considered here differs from previous work by explicitly identifying factors and quantitatively assessing their relative importance via a cost function. The cost function was used within a greedy algorithm to derive a clinical area order.

By applying the greedy algorithm on one year of clinical area transition data acquired at the Churchill Hospital, Oxford, we generated a clinically sensible roll-out order that minimises the number of “high-cost” transitions (from electronic to paper recording). Furthermore, we showed how the cost function could be extended to account for additional factors. We considered the impact of similar clinical specialties (directorates) by incorporating an additional element to the tuple that allowed us to model clinical areas with known similar clinical specialties. The inclusion of directorate had a limited effect of the proposed order, but greatly increased the number of problematic transfers.

Finally, we demonstrated how, given a proposed roll-out order, the cost function may be used to evaluate the effectiveness of the clinical area ordering and highlight areas that are likely to cause greater difficulty. Whilst the roll-out of CISs and other clinical interventions remains a complex problem, the graphical model introduced here may help in implementing and evaluating roll-out strategies objectively. The approach taken here is simple to understand, computationally light, and a useful additional tool for understanding potential problems in CIS phased roll-outs.

Contributor statement

PW and DW contributed to the study design. DW and NW developed the methodology, collected analysed the data and drafted the manuscript. All authors were responsible for drafting the manuscript. All authors read and approved the final manuscript.

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