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Intensive Care Unit Availability Indexed to Patient Complexity

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***Abstract*— In this paper, a procedure to estimate a Clinical Unit availability is presented. Service availability depends on multiple resources, some of them redundant, to function properly. However, resource consumption varies according to patient's medical condition.**

The availability of an Intensive Care Unit (ICU) depends both on basic components (electricity, water) and on requirements set by patient complexity and quantity. We propose using Diagnosis Related Groups (DRG) as an estimator of patient complexity. Accumulated DRG (DRG_a) represents the quantity/complexity combination that the ICU has to care for at any given moment. Our analysis allowed us to find the theoretical combination of patients that would collapse a clinical unit. This limit was deemed reasonable to expert advisors based on their experience at the ICU.

The study was conducted for the adult ICU at the 'Clínica Universitaria de Concepción', a teaching hospital in Concepción, Chile. Data was collected during 4 months and analyzed using reliability theory. Overall reliability and availability results are consistent with incident reports at the Clinic. The procedure and recommendations for unit design and management are applicable to Clinical Units both at early planning stages or for currently working units.

I. INTRODUCTION

Hospital and Clinics rely on many resources to deliver care to its patients. This unique combination of resources is not easily found in other industries. Supplies include electricity, cold and hot water, sewage, medical gases and data connectivity. Facility provided resources include space, temperature and humidity control, air renewal and lighting. Human Resources are required in different areas and specialties. Related only to patient care, physicians, nurses and paramedics must be present at all times. Medical equipment requirement is set by the Sanitary Authority according to the clinical unit, and is a long list of specialized machines for different clinical procedures. Failure in any subsystem implies downtime that affects patients and revenue.

This paper presents a reliability analysis of an Intensive Care Unit (ICU) considering all 'must–have' resources, as indicated by the Sanitary Authority. We classified those resources in non patient–complexity related (NPCR) and patient–complexity related (PCR). NPCR resources or subsystems are those that must be present at all times, regardless of the number or complexity of the patients. NPCR includes electricity, water, lighting and others. PCR subsystems include all those that depend on the number and complexity of patients. Some examples of PCR are ventilators, infusion pumps and nurses. A survey at the 'Clínica Universitaria de Concepción' (CUC) in Concepción, Chile was conducted to estimate availability of PCR subsystems.

It is clear that patients with different conditions need different resources allocated to their care. While a noncritical patient may only need a vital signs monitor, a critical patient may need multiple infusion pumps, a ventilator and constant medical supervision. To assess those differences, we propose using Diagnosis–Related Groups (DRG) [1]. DRG codes were introduced in 1976 to standardize medical procedure costs and reimbursements [2]. The evolution of DRG codes and associated costs has been different in each country [3]. However, in all of them, a 'base' diagnosis group is given a cost–weight of 1 and all the other cost–weights are normalized to this base. The price paid for the base group is negotiated, and all prices are set accordingly. Chile uses Spain's DRG codes and cost–weights, which are calculated based on the average cost associated with hospital procedures given a diagnosis group [4]. We propose to index PCR subsystem availability to an aggregated DRG (DRG_a) that is computed as the sum of individual DRG cost–weights for all the patients being treated in any given moment. We use DRG_a as an estimator of the overall complexity and workload of the ICU.

Patient complexity and resource allocation survey was conducted from 28 June 2010 to 28 October 2010 (123 days). This period covers the influenza season in Chile, and the clinic as a whole had its peak demand. 75 patients in the period had their DRG code assigned. Only one patient did not have a DRG code assigned due to the length of the stay.

For this analysis, we considered a failure any event that implies the clinical unit does not meet the minimum requirements set by the Chilean Sanitary Authority.

A. Reliability

Reliability analysis was conducted using reliability theory and reliability diagrams [5]. In the reliability diagram, required subsystems appear in series and redundant subsystems appear in parallel. The 'k out of n ' configuration considers the case where we have multiple (n) elements and only some of them (k) are needed.

Using

MTTR: Medium Time To Repair
MTBF: Mean Time Between Failures
MTTF: Mean Time To Fail (MTBF – MTTR)

we can compute element reliability indexes:

$$\lambda = \frac{1}{MTBF} \tag{1}$$

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$$\mu = \frac{1}{r} = \frac{1}{MTTR} \quad (2)$$

System availability is defined as:

$$A = 1 - r \cdot \lambda = 1 - \frac{MTTR}{MTBF} \quad (3)$$

Indexes for systems with elements in series are computed using:

$$\lambda_s = \sum_{i=1}^{n} \lambda_i \quad (4)$$

$$r_s = \frac{1}{\lambda_s} \cdot \sum_{i=1}^{n} \lambda_i \cdot r_i \quad (5)$$

Indexes for systems with elements in parallel in the reliability diagram are computed using:

$$\lambda_p = \prod_{i=1}^{n} (\lambda_i \cdot r_i) \sum_{i=1}^{n} \mu_i \quad (6)$$

$$\mu_p = \sum_{i=1}^{n} \mu_i \quad (7)$$

Indexes for elements with redundancy 'k out of n' are computed based on the individual element availability (A) using a binomial distribution [6]:

$$P_{k/n} = 1 - \sum_{i=0}^{k-1} \binom{n}{i} \cdot A^i \cdot (1-A)^{n-i} \quad (8)$$

$P_{k/n}$ is the probability of failure. In this case, we consider that group MTTR is the same as an element MTTR:

$$r_{k/n} = MTTR_i \quad (9)$$

and

$$\lambda_{k/n} = \frac{P_{k/n}}{r_{k/n}} \quad (10)$$

B. DRG_a

Accumulated DRG is computed as sum of the cost–weights of all the patients in the ICU at any given day. DRG code for a particular patient is assigned by the Clinical Analysis Unit after discharge. Only one patient out of 76 did not receive a DRG code by the time of this report. A typical value was used because removing that particular patient would alter the resource allocation and the availability analysis.

II. Availability analysis

Reliability diagrams and availability analysis was conducted for all resources involved in patient care in the ICU. NPCR and PCR subsystems were identified and treated accordingly.

NPCR subsystems include (Fig. 1):

- Supplies
- Facility
- Human Resources shared among patients (attending physician)

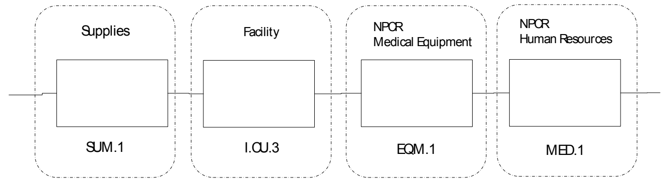

Fig. 1. Reliability diagram for subsystems not related to patient complexity.

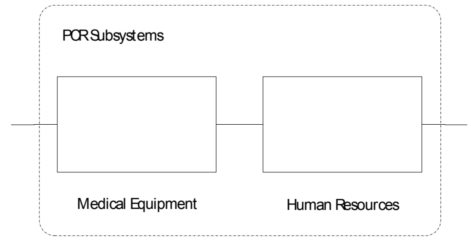

Fig. 2. Reliability diagram of patient–complexity related subsystems.

- Medical Equipment shared among patients (e.g. Defibrillator)

PCR subsystems include (Fig. 2)

- Human Resources dependent on the number of patients
- Medical Equipment assigned to individual patients

All subsystems were analyzed from 'as build' plans and on–site inspections. A reliability diagram was constructed for each one of them and overall availability was calculated. Individual elements or subsystems reliability indexes were obtained from [5], utility records and estimations from manufacturers or maintenance data.

A. Supplies

Electricity, water & sewer system, oxygen, medical air, vacuum and IT & communications systems were considered.

B. Facility

Physical space, temperature and humidity control, air renewal and lightning systems were considered in this category.

C. Human resources

Human resources are both NPCR and PCR systems. According to the Sanitary Authority only one attending physician is required every 8 ICU beds. Since CUC has 8 beds in ICU, this is a NPCR resource.

On the other hand, nurses (RN) and paramedics depend on the number of patients. Base staff is 1 RN and 2 paramedics. When the ICU has over 4 patients, an extra RN and paramedic are called in.

D. Medical equipment

Medical equipment also has to be separated into 2 groups. The NPCR group is formed by all subsystems that are required but are not related to the occupancy or complexity of the patients in the unit. This includes external pacemaker, capnograph, transport ventilator, scale and external defibrillator. The PCR group has all the equipment that is assigned to a particular patient. In this group we considered dialysis

TABLE I

CALCULATED AVAILABILITY FOR NON PATIENT–COMPLEXITY RELATED (NPCR) SUBSYSTEMS.

Subsystem	*Availability*
Supplies	0.986092
Facility	0.991360
NPCR Medical equipment	0.994276
NPCR Human resources	0.998004
Total non-indexed systems	0.969732

TABLE II

SIMULATION RESULTS OF ICU MEDICAL EQUIPMENT AVAILABILITY FOR DIFFERENT DRG_a WEIGHTS.

Patient combination	DRG_a	Availability
3 critical and 5 medium complexity	35.34	0.960293
4 critical and 4 medium complexity	40.45	0.941280
5 critical and 3 low complexity	41.06	0.937296
5 critical and 3 medium complexity	45.56	-0.043697
6 critical and 2 medium complexity	50.68	-1.039706
8 critical patients	60.90	-1.039706

machines, hemodynamic support equipment, beds, bedside monitors, ventilators and infusion pumps.

As mentioned, the ICU is prepared to admit up to 8 patients. However, there are only 5 ventilators and 20 infusion pumps. Since a patient can have more than one pump assigned to them, these 2 items become constraints related to patient complexity.

III. RESULTS

A. NPCR Systems

Results for all systems that do not depend on patient number or complexity are shown on Table I.

B. PCR Systems

The survey conducted at the clinic showed that as DRG_a increases, PCR medical equipment availability decreases. This is mainly due because infusion pumps and ventilators are used in higher complexity patients, occupying those limited resources and leaving less of them to be used as replacement.

In order to find the limit availability and to have more data, we simulated various combinations of patients for a full ICU (8 patients). Three types of patients were used, representing different patient complexities. The types were:

- Critical patient: DRG weight of 7.6, requires ventilator and 4 infusion pumps
- Medium complexity patient: DRG weight of 2.5, requires on average 2.5 infusion pumps
- Low complexity patient: DRG weight of 1.0, requires only one infusion pump

DRG_a and availability is computed for all the combinations shown in Table II.

5 critical patients and 3 medium complexity patients is the limit for this ICU. This is due to the fact that there are only 5 ventilators. When patient requirements exceed resources, the simulation shows a negative availability.

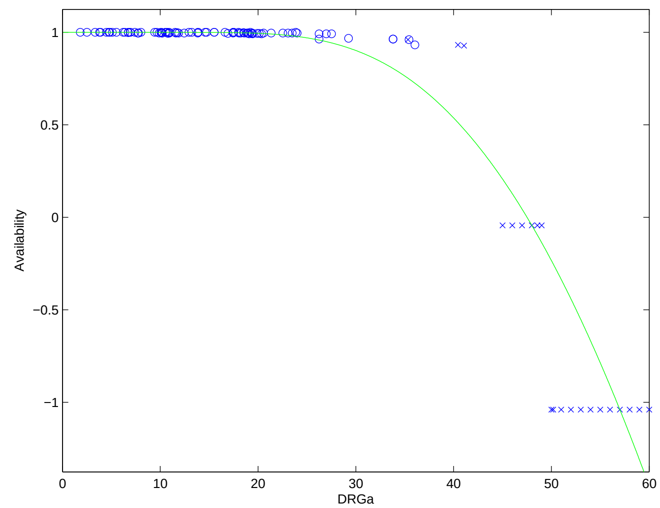

Fig. 3. Measured availability (O), simulated availability (X) and derived relationship between DRG_a and availability (–) for the PCR medical equipment subsystem.

Fig. 3 shows both the computed availability from the collected data and the estimated availability from the simulated data. The curve makes sense in that there is a sharp decrease in availability due to insufficient resources when accumulated patient complexity exceeds a certain limit. In our case, the limit is set by ventilators and/or infusion pumps. Equation 11 was proposed to model this subsystem availability.

$$A = 1 - \left[(\gamma \cdot DRG_a) \cdot \left(e^{-\alpha / DRG_a} \right)^{\beta} \right] \qquad (11)$$

The final coefficients were adjusted to:

$$\alpha = 10.77914$$
$$\beta = 14.05014$$
$$\gamma = 0.51004$$

Finally, Fig. 4 shows the combined availability of all subsystems in the ICU. NPCR components have a constant availability, regardless of DRG_a. PCR subsystems availability depends on accumulated patient complexity, and becomes zero for a combination of patients with a DRG_a of 47.

IV. CONCLUSION

As shown in Fig. 4, there is a limit to the number and complexity of the patients that can be treated in the ICU. This limit can be determined using reliability analysis of all subsystems involved in patient care. We also notice that for low complexity patients, availability is determined by the NPCR subsystems such as supplies and facility. For high complexity patients, PCR subsystems limit the ICU capacity. In this particular case, availability decreases sharply when DRG_a is over 35. Higher requirements on 'k out of n' subsystems makes them behave more like a serial system than a parallel (redundant) system.

During this study, we noticed that 80% of the time, DRG_a is under 20. This means that most of the time, the ICU limit will be set by the NPCR subsystems. A proper planning

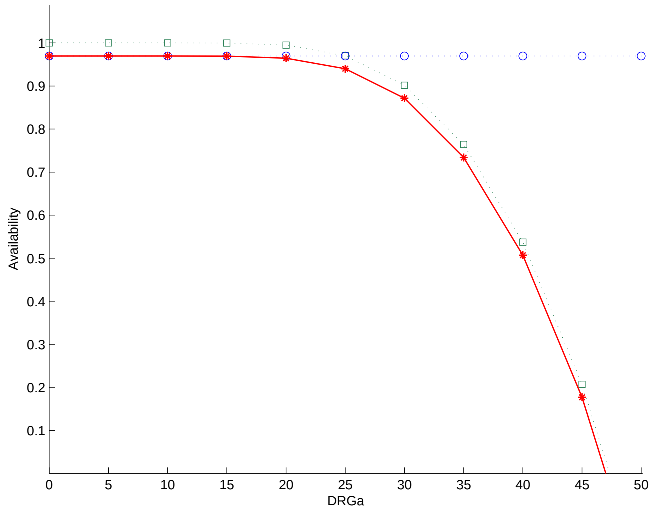

Fig. 4. Availability v/s DRG_a. Subsystems that are not dependent on patients (O), subsystems patient complexity dependent (□) and final availability combining the two components (∗).

and design of supply systems and general facility is of great importance. This can be easily done during the planning and design of a new project, but can be very difficult and expensive for existing facilities. The tools shown in this paper allow engineers to analyze and detect critical elements in the system.

During peak demand periods, it makes more sense to prepare a contingency plan for those rare events when DRG_a exceeds the unit's capacity. Increasing available units would shift breaking point to higher DRG_a values, but at great cost. A contingency plan can move this limit temporarily, for instance by reallocating resources from other units. Equipment and personnel are the key factors in these high complexity scenarios.

Finally, our approach to estimate limiting factors in a clinical unit proved useful. The results are reasonable given the amount of real–life incidents experienced during the length of this study. Simulation is the easiest way to estimate the maximum capacity of the ICU.

V. Acknowledgments

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