Analysis and Specification of Requirement Simultaneity

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Abstract. Specification requirements are typically considered and tested separately. However ambiguity can exist about which function and performance requirements need to be met simultaneously.

Traditional approaches to dealing with requirement simultaneity include generic statements that describe how requirements are to be combined, or use of mode and state diagrams. Neither of these approaches allow more complex combinations of requirements, nor allow specification of simultaneity within the relevant requirements.

The proposed approach includes analysis of requirement simultaneity and three techniques are discussed.

1. Modes and state analysis can identify groups of requirements that may be simultaneous.
2. Modelling the functional flow for a system highlights parallel functions that may need to be simultaneous.
3. Resource constraint simultaneity tables are constructed by considering each of the resource constraints that can limit the ability of a system to achieve requirements simultaneously.

Practical methods are then presented for specifying requirement simultaneity.

Introduction

The heart of a requirement specification is a set of statements about the requirements for a system – its function, performance, constraints and other characteristics.

It's usually clear to specification users that the system needs to achieve all of the agreed requirements. What is often not so clear is which function and performance requirements need to be met simultaneously with other function and performance requirements. Specification writers may trust that it is self evident which requirements need to be met at the same time. However they may find that once contracts are signed, and the system designed and built, the designer or builder unexpectedly clarifies that the system can do function A, but not at the same time as function B.

Solving this problem to ensure that a specification is clear on which requirements need to be met simultaneously can usually be done easily using the approaches proposed in this paper. Like any improvement to reducing ambiguity in a specification, the payoff can be significant, in reduced contractual disputes, or a system that better meets user needs.

Despite extensive searches using Google and in twelve requirement texts, no existing documented knowledge was found on the subject of requirements simultaneity. This paper examines some existing specification approaches, suggests techniques for analysis of simultaneity, and then provides recommendations on specifying simultaneity.

Function and performance versus property requirements

For the purpose of this paper, requirements will be divided into Function and Performance requirements, and what will, for this paper, be called property requirements.

Function and performance requirements are those that specify what the system needs to do and how well it needs to do those functions.

Property requirements specify things which should be achieved all the time, and include constraints, characteristics or quality requirements. For example the system needs to be a particular colour, size, or comply with a standard. Usually these requirements are expected to be met regardless of the functions that the system is performing as they are a fixed property of the system. [1]

This paper will address function and performance requirements only, because these are requirements which may not need to be achieved all the time, and so which function and performance requirements need to be simultaneous needs to be resolved.

From here on in this paper, any reference to *requirements* can be read as limited to function and performance requirements, unless the reference is to *property requirements*.

A specification example

An example system that will be used in this paper is a light military vehicle that can be fitted with add-on armour. Here are some sample function and performance requirements[2]:

> The Vehicle shall be Able to be fitted with Armour.
>
> The Vehicle shall be Able to tow a Trailer.
>
> The Vehicle shall carry a pallet loaded with 750 kg of cargo.
>
> The Vehicle shall ascend a 15% grade at not less than 40 km/h.
>
> The Vehicle shall sustain an average speed of not less than 100 km on highway course XYZ.
>
> The Vehicle shall be Able to be transported on a Hercules aircraft.

It's reasonably clear that some of these will not be simultaneous – the vehicle won't be ascending a 15% grade and travelling at 100km/h on a highway at the same time, nor will it be travelling at 100 km/h while transported on an aircraft. What is not clear is whether the Vehicle needs to be able to be simultaneously fitted with armour, tow a trailer, and carry a 750 kg pallet. And does it need to be able to be transported on a Hercules aircraft when carrying cargo, armour and towing a trailer?

Where are we at?

Are individual requirements in a set simultaneous?

An important first question is "*Are requirements in a set of requirements simultaneous?*" Specification authors may assume that it is self evident that some requirements are simultaneous, and conversely that some are not. These assumptions about which

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[1] If there is any doubt as to whether achieving these property requirements is independent of other requirements or independent of the modes of use of the system, then there may be a benefit in specifying that the property requirements are achieved in all cases.

[2] Note that these are an incomplete sample set to illustrate the simultaneity issues only.

requirements are simultaneous are exactly the assumptions that can cause ambiguity and consequent problems.

The short answer to the above question is "*No, unless they are specified to be*". Each requirement is verified by an individual test. So when the test agency comes to verify whether the system meets the requirements, they will go through the requirements one by one and test each according to the verification method stated.

If there are statements in the specification that specify that certain requirements are combined then the testing should reflect this. [3]

Traditional approaches

In evaluating traditional approaches to requirements simultaneity there are two aspects to consider. The first aspect is how simultaneity is specified – in other words, how does a specification tell the reader which requirements need to be simultaneous. By reading a specification, the approach taken to specifying simultaneity can be easily seen.
The second aspect is much harder to evaluate, and that is how the specification writer analysed which requirements should be simultaneous. To evaluate the analysis method, the writer needs to be interviewed or observed, and the ability to draw conclusions without a thorough study is limited. Because of this difficulty, the analysis methods described here may not accurately reflect the methods typically used. As mentioned in the introduction, however, an absence of documented knowledge on this topic indicates that techniques are not well established, and this concords with the author's experience. Following are common approaches to specifying and analysing simultaneity that the author has observed.

Generic Statement

A common approach to specifying requirement simultaneity is to include generic statements. These statements can be intended to be a "catch-all" by overspecifying the simultaneity in the hope that it covers where it is actually needed. Some real life examples the author has seen are these statements included near the start of specifications:

> Example 1. *All requirements shall be met concurrently.*
>
> Example 2. *All requirements shall be met in sea state 6.* [4]

There are major problems with the generic statement approach. Two of the most significant are:

Problem 1: The statement may be incorrect. In example 1, saying that all requirements must be met concurrently is most likely to be totally unachievable. Most systems perform a variety of functions that cannot occur at the same time, so attempting a catch-all over-specification will probably result in the generic statement being contractually unenforceable. The requirement in example 2 is also incorrect, as many ship functions will not occur in such an extreme sea state, such as refueling, helicopter landing, docking, and so on.

Problem 2: The verification of generic statements can be ambiguous or else quite onerous. Example 1 can be interpreted as meaning that every combination of

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[3] There is a risk in this approach that test agency does not notice statements that combine requirements, or provide overriding conditions, especially if these statements are not located with the requirements.

[4] This is a requirement from a ship specification. Sea state 6 is classified as very rough, with waves from 4m to 6m.

requirements, including property requirements, needs to be verified. Example 2 effectively asks for every requirement in the specification to be verified in a sea state 6 condition, whether it relates to the colour of power wiring or operation of a radar system.

Mode and State Analysis

Some systems engineering and specification standards require definition of modes and states of a system (Australian DoD, US DoD 94, EIA-632-1998, IEEE 1220-1998). A state or mode is a condition of a system that occurs during its operation. For our vehicle system example, possible modes or states could be Road Travel Mode, Air Transport Mode, Armoured State etc. In Australian Department of Defence specifications a mode and state diagram is often required to show which states or modes can exist simultaneously (Australian DoD). Following is a simple mode/ state diagram for the Vehicle example:

	Road Travel	Air Transport	Armoured	Recovery
Road Travel	-	N	Y	N
Air Transport		-	Y	N
Armoured			-	Y
Recovery				-

Table 1. Example Mode and State Diagram.

Note that the bottom left corner of the table need not be filled out as it just mirrors the top right corner.

By itself a mode and state diagram gives a very limited view on simultaneity at the individual requirement level. To have any value, the applicable modes and states for each requirement need to be stated. While the Australian Defence document DID-CDG-DEF-FPS-V1.2 implies that states or mode should be applied to each requirement[5] unfortunately, in the authors experience within Australian Department of Defence specifications, this is very rarely done.

Ad-hoc Analysis

Perhaps the most common analysis approach, in the author's experience, is best described as ad-hoc. There is no structured or planned simultaneity analysis approach used – if the specification writer notices that simultaneity may be an issue for requirements, then he/she includes this in the requirements accordingly. In many cases this approach can work, particularly for simpler specifications, or specifications for off-the-shelf systems. Where systems are more complex or developmental, an ad-hoc

[5] Para 6.2.3.4.2 states "Each state or mode definition shall support the assignment and definition of functions in the FPS. These definitions should be used to identify the states and modes to be supported by the Materiel System or its relevant subsets. A table or other method may be used to show the correlation of states and/or modes to requirements or groups of requirements either directly in this paragraph or in an annex referenced from this paragraph. Alternatively, each requirement may be directly annotated with the applicable state / mode information."

approach to requirement simultaneity will involve higher risks of problems occuring during system design or build.

Some Ideas For Improvement

Given an apparent lack of sound existing techniques for dealing with requirement simultaneity, a process is provided here, which uses two steps:

Step 1 - Analysis. Determine which requirements should be simultaneous.

Step 2 – Specification. Correctly specify simultaneity in the requirements.

Requirement Simultaneity Analysis

Just as proper analysis is needed to determine what the system requirements are, requirement simultaneity needs to be analysed before it can be specified.

There are three principal reasons why requirements may or may not be simultaneous, and these reasons can be used as a basis for simultaneity analysis.

> **Reason 1** - the system operates in different modes or states, and some requirements will apply to some modes but not others.
>
> **Reason 2** - requirements are time sequenced. The system needs to perform a particular sequence of steps which may be in series or in parallel.
>
> **Reason 3** - the system cannot achieve requirements simultaneously due to a system resource constraint.

The first two reasons are driven by the user and how they intend or want to use the system. Gaining a clear understanding of how the user will use the system, through considering user scenarios or use cases provides the foundation for analysing what users want to be simultaneous. The third reason relates to the system and the realities of how it may be limited in meeting what the users may ideally want.

Each of the three reasons will now be developed into a simultaneity analysis method.

Method 1 - Modes and states analysis

The mode and state analysis technique was introduced in the "Traditional Approaches" section on page 4. To be of value in analysing simultaneity, applicable modes / states need to be identified for each requirement. Table 2 provides an example.

Serial	Requirement	Applic modes/states
A	The vehicle shall be Able to be fitted with Armour	Road travel, Armoured, Recovery.
B	The vehicle shall be Able to transported on a Hercules aircraft.	Air transport
C	The Vehicle spot light shall illuminate the area to the rear of the vehicle	Recovery, Armoured
D	The vehicle winch shall pull the vehicle at not less than 0.5 m/s	Recovery, Armoured

Table 2. Example Requirements with Mode and States Assigned.

Assigning modes / states for each requirement does not fully define simultaneity – but it does tell us that:

- requirements that share a mode or state *may* be simultaneous. For example in table 2, serials C and D may be simultaneous because the same mode / state applies to both requirements.
- a requirement in one mode / state is *not* simultaneous with a requirement in mutually exclusive mode / state. In table 2, serial B will not be simultaneous with serials A, C or D, because Air Transport applies to B, while Road Travel, Armoured and Recovery modes / states apply to A, C and D, and these modes / states are mutually exclusive with Air Transport mode / state.

What a modes / states analysis does not tell us is:

- If requirements that share mode / state are simultaneous. In table 2, we don't know if serials C and D are simultaneous – they may happen one after the other.

So the mode and state technique only provides a shortlist of requirements that may be simultaneous and determining actual requirement combinations needs to rely on other techniques, including the following two methods.

Method 2 - Time sequenced functions

Modelling a system or user operational scenario to produce diagrams such as functional flow block diagrams or activity diagrams can highlight functions that will be in series or parallel. Functions in parallel with a logical "AND" relationship show a need for simultaneity. Here is a partial example for the light armoured vehicle, showing an operational scenario of recovering a bogged vehicle at night (drawn using no particular notation standard):

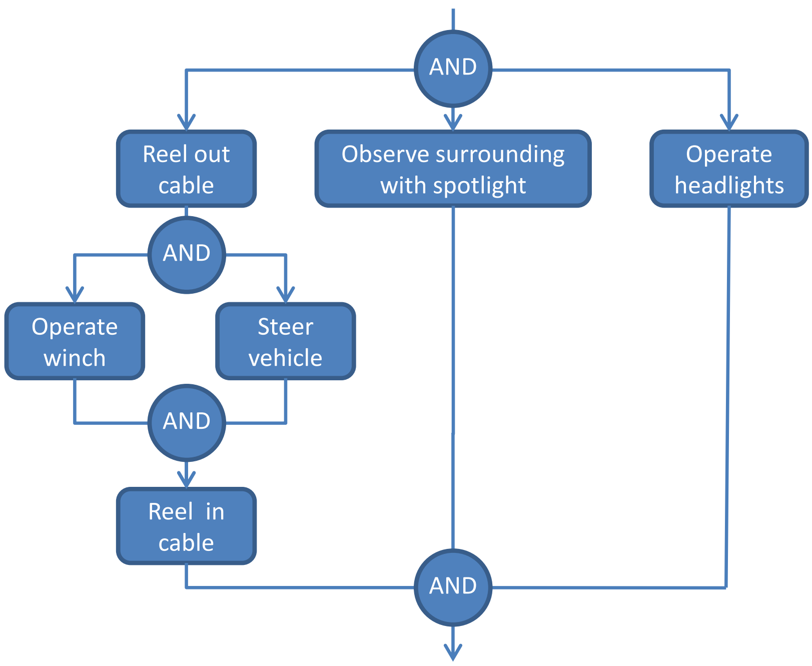

Figure 1. Flow Diagram for Scenario of Recovering a Bogged Vehicle at Night

This example shows that the winch, steering, spotlight and headlights need to be used simultaneously. The cable also needs to be reeled in or out at the same time as using the spotlight and headlights.

Method 3 - System resource constraints

Method 3 uses the concept of resource constraints to identify which requirements that the user may ideally want to be simultaneous, but may involve additional cost or system tradeoffs.

For the Vehicle example requirements, the resource constraint is primarily one of vehicle load or weight. As armour, cargo, or a trailer are added some of the limited capacity of the vehicle to carry a load is used up. Another resource constraint will be engine power, which will affect the ability of the vehicle to climb hills, or overcome air resistance.

Other resource constraints that may be experienced by land vehicle systems could include:

- Electrical Power
- Available personnel
- Space

Resource constraints in a communication system could include:

- Bandwidth
- Power
- Display area
- Number or size of control buttons
- Heat dissipation

For a military ship, radar capability can be an important resource constraint, which will affect the ability of the ship to simultaneously detect an incoming missile, monitor helicopters landing, or detect the presence of small ships at a distance.

Using resource constraints to analyse requirement simultaneity is, as far as the author knows, a new method, so this method is described in detail in the following section.

Using the Resource Constraint Analysis Method

To perform the resource constraint simultaneity analysis, requirements that are affected by the resource constraint need to first be identified. This is done manually by considering each requirement, and whether it will be affected by the identified resource constraints. A substantial number of requirements will be property requirements and these can be quickly excluded from any analysis.

A simultaneity table is produced for each resource constraint. The requirements that are affected by the resource constraint are listed in columns, and the required combinations are identified using crosses. Table 3 below shows an example simultaneity table for the load resource constraint. Row C shows that the vehicle needs to ascend a 5% grade at more than 40 km/h while carrying armour, towing a trailer, but not while carrying cargo. The decision of whether a combination of requirements need to be simultaneous will be via the same process as the requirements were generated, which will typically be a combination of user input, feasibility, and engineering judgement.

Attributes can be assigned to each requirement combination. The priority for row C is assigned as Low. Additional columns can be included for other attributes, such as rationale, or a reference to the specification clause ID (once written).

Requirements – vehicle load constraint							Attributes (can also include rationale, ID)	
Row	**Base [6]**	**Carry Armour**	**Tow Trailer**	**Carry Cargo**	**Ascend 5% grade**	**Transport by Air**	**Priority**	
A	X	-	-	-	X	-	High	
B	X	X	-	-	X	-	High	
C	X	X	X	-	X	-	Low	
D	X	X	-	X	X	-	Med	
E	X	X	X	X	X	-	Low	
F	X	X	-	-	-	X	High	
G	X	X	X	-	-	X	Med	
H	X	X	X	-	-	X	Low	
I	X	X	-	X	-	X	Low	
J	X	X	X	X	-	X	Med	

Table 3. Simultaneity table for vehicle load resource.

Another key resource constraint for the vehicle could be electrical power. A separate simultaneity table would consider requirements for operation of vehicle ancillary systems, such as a winch, radio, headlights.

Requirements – electrical power constraint					Other attributes (eg rationale, ID, criticality)
Row	**Operate winch**	**Operate Radio**	**Operate head lights**	**Priority**	
A	-	-	-	High	
B	X	-	-	High	
C	-	X	-	High	
D	X	-	X	High	
E	X	X	X	Low	

Table 4. Simultaneity table for vehicle electrical power resource.

Although it is possible to consider more than one resource constraint per table, for most

[6] Base here means the vehicle base configuration, without armour, trailer or cargo.

systems this will result in an unmanageable number of columns.

Advantages of Resource Constraint Analysis Method

Using resource constraint simultaneity analysis has two key advantages that make it attractive:

1. It can be applied at the time of writing a specification, or when reviewing a completed specification. By contrast, the mode / state and time sequenced functions techniques rely on systems engineering work that should precede writing a specification, but in the author's experience is not often done.
2. Resource constraints are commonly what lead to the system designer or builder making compromises that the customer or user may not want or have expected. Designers or builders often tend to want to make things smaller (or possibly larger), less strong, less powerful, or lower bandwidth to reduce the cost of a system. There may also be trade-offs required between competing requirements, such as load capacity vs fuel consumption, or battery capacity vs weight. Anticipating unwanted compromises and ensuring that requirement combinations are properly specified can head off contractual arguments or dissatisfied users.

Resource Constraint Analysis Method Limitation

To be able to identify resource constraints requires that the physical form of the solution is known and at least resonably well understood. However if the specification is truly solution independent, then the physical solution may not be known. In this case, instead of considering resources, the analysis should consider functions that the system must perform. For the vehicle load example the function may be to "carry". Requirements that either require the system to carry something, or impact on the ability of the system to carry, will be considered in one simultaneity table.

Which method?

So which of the three methods should be used? The usefulness of each method will depend on the system - all three methods can potentially uncover requirements that should be simultaneous. So if in doubt try all three, and don't hesitate to consider other approaches as well.

Specification of Requirement Simultaneity

The diagrams and tables produced from the requirements simultaneity analysis are inputs to the specification only, and are not necessarily included in the specification. Preferred, non-preferred and acceptable methods for how information in the simultaneity diagrams and tables are applied to the specification requirements are discussed in this section.

Non-preferred Method

It is tempting to specify the combinations of requirements that must be simultaneously achieved by use of a table or matrix (such as the resource constraint simultaneity table) as many combinations can be shown clearly in a small amount of space.

However this method has some key disadvantages:

- in most natural language[7] specifications, the format is typically one row per requirement, and requirements stated as text in one column. Introducing a table or matrix format is not easily compatible with this format, particularly where a spreadsheet or database format is used;
- the table is not a natural language statement, but rather a series of crosses against headings. This therefore may give rise to ambiguity if the interpretation of the table or the table headings is not properly explained in the specification.

If a simultaneity table is included within the specification it is preferred that this be for information only, and not define requirements. Care will then be required to ensure that the table aligns with the specified requirements.

Preferred Method

The preferred way of specifying requirement simultaneity in a natural language specification is to include a requirement for each combination of other requirements. This approach has advantages of:

- format compatibility between requirements;
- allows the use of the same attributes for all requirements;
- the text of the requirement provides all the information needed within the requirement, and does not rely on other requirements or advice statements for its interpretation.

Table 5 shows examples of requirements that specify a combination of requirements.

Requirement	Priority	Verif Method	Rationale
The Vehicle, when fitted with Armour and carrying Cargo, shall ascend a 5% slope at not less than 40 km/h.	Medium	Test	Because ...
The Vehicle, with the engine running, shall power the winch, radio and headlights, without draining the battery.	Low	Analysis	Because ...
The Radio shall display the following information simultaneously: • battery status; • frequency; and • transmit mode.	Medium	Demonstration	Because…

Table 5. Examples of specification of simultaneous requirements.

There can sometimes be a large number of viable requirement combinations, which will create a large number of requirements. Possibilities for reducing the number of

[7] Natural language specifications primarily use words to articulate the requirements. Other specifications types can use mathematical methods, diagrams, models and programmatic languages.

requirement combinations include specifying the worst case combinations only, and specifying representative sample combinations. For example, for the electrical power analysis in table 4, it will be low risk to exclude requirements in rows A and B, as these are superseded by the High priority requirement in Row D. If the vehicle alternator can power the vehicle with the winch and headlights operating, then it will be able to power the vehicle with no other systems operating, or the vehicle with the winch operating.

The decision about whether it is necessary to include a requirement combination is the same for any other requirement, and is the answer to the question "Does the value of including the requirement exceed the cost of including the requirement?" The value will be primarily from the reduced risk that the system cannot perform the requirement combination, while the cost will be the cost of writing, reviewing, managing, negotiating, and testing the requirement throughout the system development.

Acceptable Method

Where a particular requirement, or set of requirements, is simultaneous with numerous other requirements, then specifying each combination in full can reduce readability. In this case it is may be preferred to use a modifying clause that applies to multiple requirements. The disadvantage of this approach is that the requirements are not self-contained, and must be read in conjunction with other requirements.

Table 6 shows an example of use of a modifying clause. In this example clause 3.1 is the modifying clause, while 3.2 is the clause that it modifies. In a real specification the modifying clause would usually modify two or more other clauses.

Clause	Requirement	Priority	Verification Method	Ref clause
3.1	For all requirements in this section, the Vehicle is fitted with Armour and towing a Trailer.	Advice	Not required	
3.2	The Vehicle shall ascend a 15% slope at more than 40 km/h.	Medium	Test	3.1

Table 6. Example of use of a modifying clause

If this approach is used, then the risk of the modifying clause not being considered in the interpretation of a requirement can be minimised if a formal linking or referencing system between requirements is used. This could be by use of an attribute that identifies any related clauses, as shown in the "Ref Clause" column in the Table 5 example.

Summary

Requirements are not simultaneous with other requirements unless they have been specified to be.

To ensure that requirements that need to be achieved simultaneously are clearly specified as such, a two step process can be used, comprising analysis and specification.

Techniques for analysis that can be used are modes and states analysis, functional flow diagrams, and analysis of resources constraints. The resource constraint method considers each resource that will constrain the ability of the system to achieve requirements simultaneously. The output of the resource constraint analysis is a table for each resource constraint that shows which combinations of requirements are needed, and attributes associated with the requirement combination.

The preferred method for specifying requirement simultaneity is to include a requirement for each combination of other requirements. This allows compatibility with the format of other requirements, use of the same attributes as other requirements, and encapsulates all information within a single statement.

There is, unfortunately, no silver bullet method that will ensure that system customers don't get unpleasant surprises when systems cannot meet requirements simultaneously. Careful thought is needed to work out and specify which requirements need to be simultaneous, but the payoff will be more satisfied system users and fewer project issues.

References

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Biography

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His experience and interest in specification writing and system acquisition comes from his work in introducing new manufacturing systems, and more recently in Defence acquisition in the Land environment. Over the last 7 years, Michael has written specifications for a number of land vehicle systems and modules, including light vehicle modules, mobile crane, container side loader, C4I integration, and aviation refuelling vehicles. He has also reviewed specifications covering military vehicles, vehicle modules, C4I integration, UAVs, weapon systems, forklifts and packaging systems.