SYSTEMS ENGINEERING IN MARKETING & ECONOMICS OF AERO ENGINES

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Abstract

Today's general aviation aircraft are being retained in services well beyond the lifecycle anticipated by their manufacturers. While some airframe aerodynamic refinements can be applied to improve performance, available engine technology is stuck in the pre 1950s. This lack of advancement is failing to meet modern environmental requirements particularly regarding fuel efficiency, noise and air pollution, as well as the overdue elimination of leaded fuels.

This paper is concerned with the application of Systems Engineering (SE) methodology to the need for maintaining, upgrading/retrofitting the world's GA aircraft, and more particularly their engines. Discussions in this paper focus on using SE techniques to define needs that leads to optimising the confidence and predict-ability of forecast demand.

1 Introduction

Following the 1980s' product-liability issues in USA, manufacturers had significantly curtailed production of reciprocating (aero) engine aircraft. Traditionally, ground and aircrews attain their initial training in general aviation (GA)—aviation's long-term viability ultimately depends on a healthy GA sector with a full range of aircraft, especially piston powered singles and twins.

Since USA has ≈75% of all GA aircraft and by far the majority of manufacturers, USA aviation policies prevail throughout the industry. One issue is the elimination of leaded aviation fuel in USA.

These issues would indicate particularly the need to retrofit, or significantly modify, the engines of current GA aircraft to use unleaded fuels—motor spirit (mogas), 82UL avgas, a yet-to-be-developed 100UL avgas, or aviation turbine fuel (avtur). Application of Systems Engineering (SE) methodology necessitates that acquisition evaluation for GA aircraft replacement/upgrade should consider future available fuel types.

Due to aircraft replacement costs and cutbacks in their manufacture, GA aircraft are retained in-service well beyond the lifecycle intended by their designers/manufacturers. Earlier research [1] identifies that replacement/upgrade aero-engines may be acquired either from one of the two established USA companies (Lycoming or TCM) or from alternative/development manufactures.

This study applies SE to the concept, exploration and definition phase of aero engines needs, reviewing the opportunities for and viability of alternative manufacturers. Initially the applications for these aero-engines will likely be the retrofit/agricultural sectors. Furthermore, mainstream USA GA aircraft manufacturers are unlikely to use engines that are either non-certificated or from unproven manufacturers. Accordingly, any new engine needs proving in related markets before their manufactures can anticipate acceptance by mainstream GA aircraft manufacturers.

This and other research by the authors, including detailed case studies, indicates demand could sustain engineering and

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manufacture of alternate aero-engines. Viability, however, depends on production-costs and cost-effective adaptations/applications (ie range of rated-power, aspiration method and aircraft-type application). In discussing these opportunities in aero-engines/components particularly for GA, this paper embraces

- Systems Engineering—needs analysis
- General Aviation—national/international fleet composition & aircraft utilisation
- Propulsion issues—regulation on fuel additives, and environmental pollution (noise & emissions)
- Lifecycle cost
- Marketing and economics

2 Systems Engineering—needs analysis

Too often aircraft/aviation manufacturers devote resources to 'pet projects' without properly researching market need and future trends. Applying structured and disciplined SE process ensures products and systems responsive to customer needs and competitive in the global economy. This paper broaches the application of SE methodology to concept exploration & definition of aero engine manufacture. The iterative SE process to define requirements includes

- Need/Deficiency(s) Identification,
- Research—patents/regulations, Papers/Reports, Surveys/statistics,
- Analysis (Trend/Matrix/Market), &
- Benchmarking.

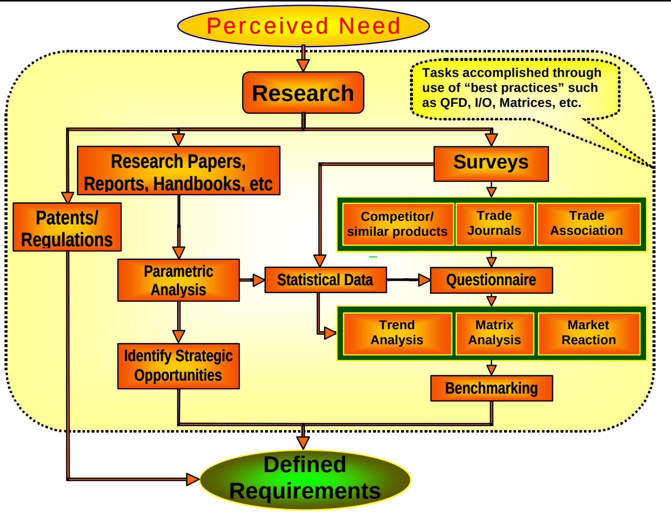


Diagram 1: *Needs analysis & requirements definition*

Adopting Verma & Fabrycky's [2] needs analysis and requirements definition methodology as depicted in diagram 1 should

- provide better indication of technical development directions/imperatives
- more reliably satisfy customer needs
- more confidently predict project viability.

Applying these principles for example to the marketing and economics of aero engines for GA should therefore aid in determining where research and development effort should focus. The first step in the procedure is to identify prospective clients. GA, unlike commercial air transport, consists of a multiplicity of stakeholders including aircraft owners/operators, maintenance organisations, pilots, passengers/customers, etc. Hence it is not practical survey a sample group to ascertain the need/s (if any) for new and improved aero engines. Surveying (per the SE needs analysis process) therefore must start with dissection and analysis of the aerospace industry (emphasising the GA sector) in order to identify potential clients and define their needs.

3 General Aviation

There is no internationally accepted definition of the distinction between general aviation and air transport—ICAO adopting the commercial/non-commercial distinction, while the US aviation industry separates the two by normal use of aircraft type being Regular Public Transport (RPT)/non-RPT. For the purpose of our 'needs definition', the US interpretation is more appropriate. The diagram 2 depicts a generic description of the aerospace industry, with particular emphasis on fixed wing GA aircraft—likely application for any new aero engine technologies. It should be recognised that while engine technology for smaller GA rotary wing aircraft is similar to that for fixed wing, the certification needs dictate that this would be a later consideration—since proportionately there are significantly fewer rotary wing aircraft.

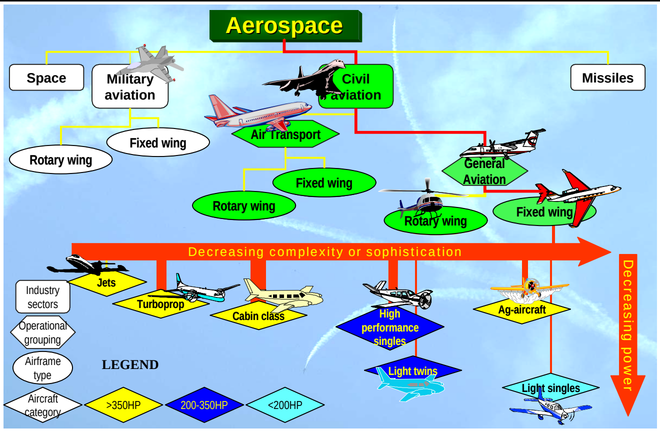
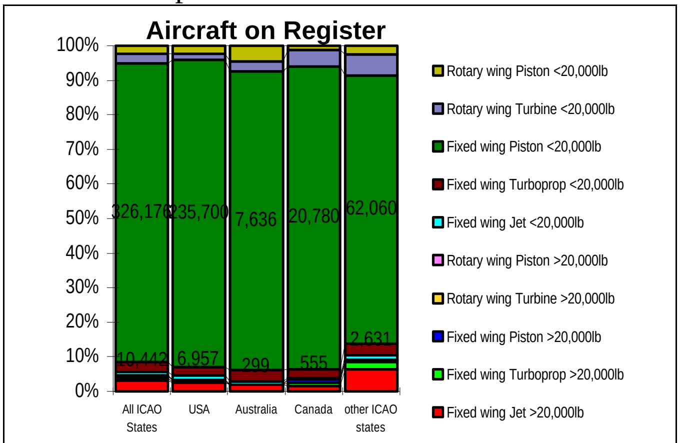


Diagram 2: *Aerospace industry dissection*

On the basis that modern reciprocating engines can be effective up to 750hp (while turboprop are more appropriate at 750shp and greater), diagram 2 suggests future aero engine application is likely to encompass cabin class and light twins, high performance singles, and agricultural aircraft types. To a lesser extent, light singles and small turboprops may also be appropriate target markets.

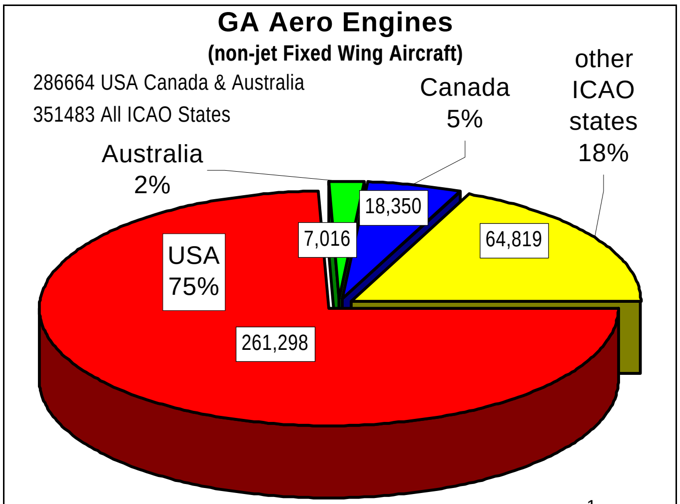
3.1 National/international fleet composition

Still in the SE identification process, additional analysis helps identify potential clients and their needs. Graph 1 shows the ICAO breakdown of aircraft categories for various ICAO states. From this comparison and also other work [3] there is good correlation between states in percentage of each class, especially so for GA fixed-wing in USA Canada & Australia. Given this relationship, detailed data from one may be used as the sample for the statistical/trend/matrix analysis of the 'needs definition' process.



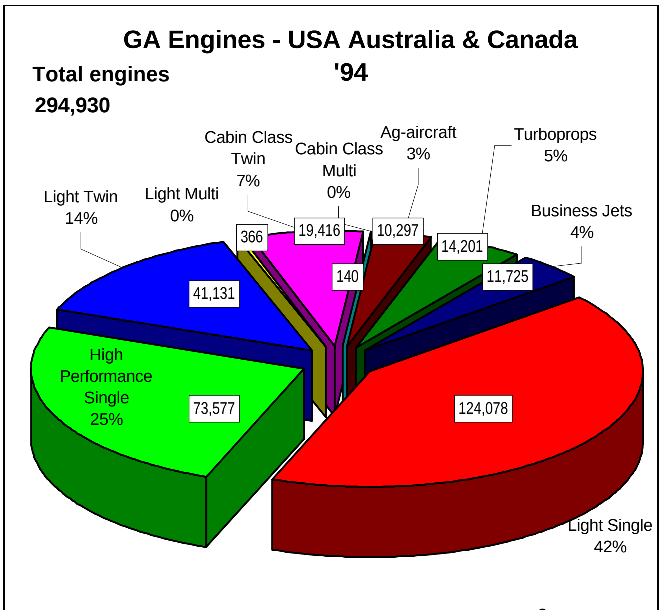
Graph 1: *Aircraft on Register- ICAO states*[1]

In graph 2, USA Canada and Australia have ≈286,500 engines used in ≈258,500 GA fixed-wing aircraft, representing >80% of all ICAO aircraft/engines in this the major sector.



Graph 2: *Fixed wing GA aircraft of ICAO states*[1]

Graph 3 shows USA, Canada & Australia aircraft categories significant to this study, including engines in Ag-aircraft, Cabin Class & Light Twins, High Performance & Light Singles, & Turboprops.

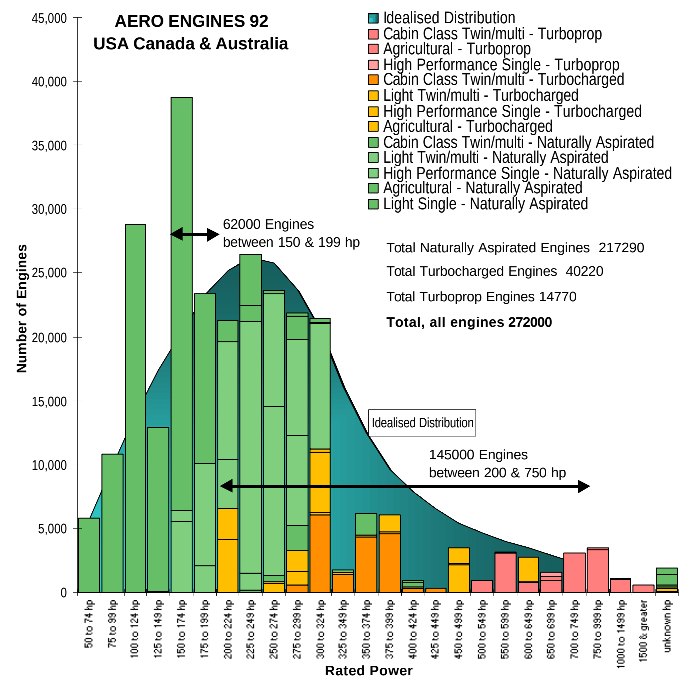


Graph 3: *Aircraft & Engines in Categories*[2]

The next logical step in the continuing data analysis stage would incorporate more detailed research into the aero engines in use.

1 Data source: *ICAO Digest 382 - Civil Aircraft on Register 1991*. International Civil Aviation Organisation, Montreal, CANADA, 1992

2 Data source *The* **AIRPAC** Statistical Newsletter™ Airpac Inc, Oklahoma City, USA, 94



Graph 4: *Aero* Engines in fixed wing GA aircraft of USA Canada & Australia

Concatenation of the findings (displayed in graph 4) and incorporating earlier research [4] shows naturally aspirated (green) turbocharged (orange) & turboprop engines (red). Hatching identifies the category of aircraft in which the engines are fitted— light singles (horizontal), agricultural (vertical), high performance singles (diagonal down to right), light twin (diagonal down to left), and cabin class twins (hash).

The lesser numbers of engines in the power range 325-449hp is due mainly to the predominant use of TCM & Lycoming horizontally opposed engines that were not available >425hp and had been perceived by aircraft owners/operators and maintenance personnel as unreliable/costly >325hp. This effective 'non-availability' has constrained aircraft manufacturers over the years to produce planes with power requirements in the attainable range. However, many aircraft designs could accommodate engines of higher power output than are currently fitted.[3]

The predominance of existing engines (turbocharged and naturally aspirated) between 150-325hp, together with the possible demand for engines from 325-425hp indicates the rated-power range for any new aero engine (allowing for probable power-upgrade at retrofit). These engines are used mostly in high performance singles, and twins (light and cabin class). This 'gap' in available power may provide the opportunity for new higher-powered engines (potentially 50,000 unit) to be incorporated in new aircraft designs—additional to the retrofitting opportunity. New engines, such as the recently TCd Orenda V8 (complimented with V6 and V4 variants) could be well placed to fill these needs.[4]

The smaller but still significant bracket 425-725hp (750shp) may also be retrofit potential. These engines are mainly used in ag-aircraft and turboprops. Most light singles (>150hp engines) will be better retrofitted with updated TCM/Lycoming or alternative Rotax/Norton/Canadian Airmotive, etc.

Based on the preceding review, it can be concluded that ***new engines*** and overhauling of existing aircraft engines are required in large numbers world wide, albeit in a variety of rated power/aspiration method combinations. USA, Canada & Australia annual total new/overhauled engines is ≈4,500 turbocharged and ≈23,500 naturally-aspirated.

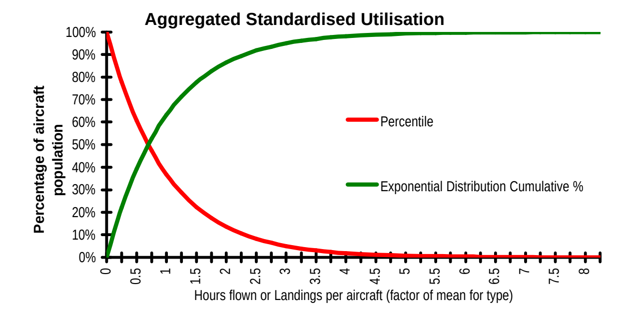
3.2 Aircraft utilisation

The owner/operator's return on investment for retrofitting aero engines is related to the aircraft utilisation. Thus our SE research into aero engines necessarily involves studies of hours flown and typical flight times for each aircraft type.

Derived from other work by the author, graph 5 shows the relationship between the percentage of an aircraft type and the factor of mean for number of hours flown.

3 From discussions with Dr H Millicer dec. (RMIT) C Nicholson (Gippsland) J Kosier (Schweizer) W Hogan (Cessna) & J Clay (Beechcraft).

4 See appendix A for summary of engine manufacturers.



Graph 5: *Aircraft Utilisation Factors*

Necessarily abbreviated for this paper, more detail is available from the author's consultancy. Suffice to say that before manufacturers/developers launch in great expense in design, TCs, STCs and manufacture of new aero engines, accurate prediction of sales revenue would be fundamental. Essentially the candidate retrofit aircraft should show an owner/operator a financial advantage—how much they save per hour times number of hours flown.

4 Propulsion Issues

Utilising the SE 'needs definition' process for the aero engine example would dictate inclusion of propulsion issues. Important among these are

- Available Fuels, and
- Environmental Pollution.

4.1 Fuels Available

Reciprocating aircraft engines currently in service were designed to use one of the then available fuels (predominantly 80/87 & 100/130) and now must be operated on mogas, 82UL or 100LL (avtur availability for turbine engines will see no change in the foreseeable future). Significantly, the 1990 Clean Air Act (USA) requires

- elimination of lead from fuels by 1/1/96
- new & re-manufactured engines sold in USA after 1/1/92, be certified for unleaded fuels[5].

Additionally, the Montreal Protocol mandates the elimination of methyl bromide compounds (100LL combustion by-products) from GA, by 1998 [5]. After 10 years in development, Unleaded 82UL avgas was certified mid 1998 to replace 80/87 (for low-compression & carburetted engines) yet still no suitable substitute for 100LL or 100/130 avgas. With mogas now required by EPA to contain zero lead, the oil companies can no longer run 100LL through any of their pipelines. So distribution of 100LL must be via tanker truck because it contaminates the pipe with lead that then shows in trace quantities in other products. Furthermore, the production of 100LL (the only product with highly toxic tetraethyl lead) requires the refineries to perpetuate costly environmental protection procedures and equipment which they could long-since have abandoned if it weren't for 100LL.[6]

Many earlier and some later engine designs (originally TCd for 80/87 Avgas) may be eligible to use either mogas or the new 82UL avgas (subject to STC and sometimes modification[7]). These STCs apply mainly to carburetted low-compression engines ≤200HP. Obviously high compression fuel injected turbocharged engines are not presently able to meet these fuel-type requirements.

4.2 Environmental Pollution

Noise generated by aircraft is increasingly subject to legislative controls. Controversy rages over noise and emission control/legislation for instance the US/European Union (EU) dispute over environmental controls, that could see Concorde banned from US airspace. The issue revolves around retrofitting US aircraft that fly in Europe with "hushkits" devices designed to quiet engine noises. The EU wants to ban aircraft with hushkits, alleging that even though the kits control noise pollution, they don't control air pollution [6]. While this issue relates to heavier jet aircraft, there is increasing pressure to have GA aircraft meet stringent targets. If owners/operators cannot meet targets, local airfields will more regularly be closed, as has already begun in USA.

The propulsion system is the primary source of this noise, so for GA this trend will in the future lead to lowering propeller tip

5 The EPA issued an exemption for light aircraft engines based on efforts to develop a replacement fuel

6 Busch M, *High Avgas Prices.* AVweb 23 Mar. 1998

7 Appendix B lists the EAA's 1999 Mogas/82UL STCs

velocities in current and foreseeable engine/propeller systems—perhaps reduction drive systems, lower crankshaft speeds, smaller diameter multi-blade propellers, etc. This may present the best market opportunity for newer aero engine designs—adopting cleaner fuels and combustion techniques and more advanced reduction/propeller systems than is practical to adapt on existing engines.

5 Lifecycle cost

Aerospace engineering/management are already utilising lifecycle costing in their design and manufacturing processes. Usually in SE, lifecycle refers to the stages through which management progress and is aimed at producing the finished product (ie system lifecycle).

Discussing lifecycle in the context this case study SE ‘needs definition’ process, we are referring to the new longevity of aircraft. Nicholas [7] (refer diagram 3) describes these phases of the life cycle as comprising conception, definition, acquisition, and operating, each having its own subset. As part of the ‘needs definition’ we should consider the cost/benefit for ‘client’ owners/operators in our ‘system improvement’ particularly with respect their acquisition and operating phases.

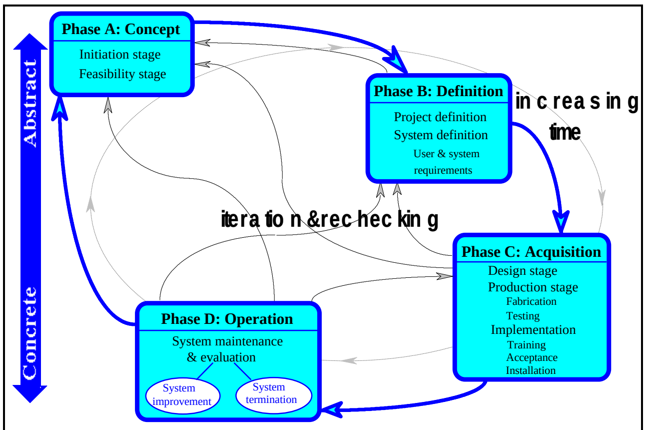


Diagram 3: *Needs analysis & requirements definition*

This process, involving the parametric analysis of projected aircraft performance together with the cost analysis, must show benefit in sufficient numbers for project viability.

6 Marketing and economics

Contrary to common belief successful marketing commences with ‘needs definition’. Aaker and Day [8] describe a SE procedure for planning, designing, and implementing marketing research. Applying the technique illustrated in diagram 4 to this case study encompassed aspects of marketing including:

- Marketing Research
- Analysis of the raw data
- Identify candidate aircraft for retrofitting with new aero engines
- Identify potential new aircraft designs, and
- Trends for growth and change in aircraft fleet composition, and activity levels.

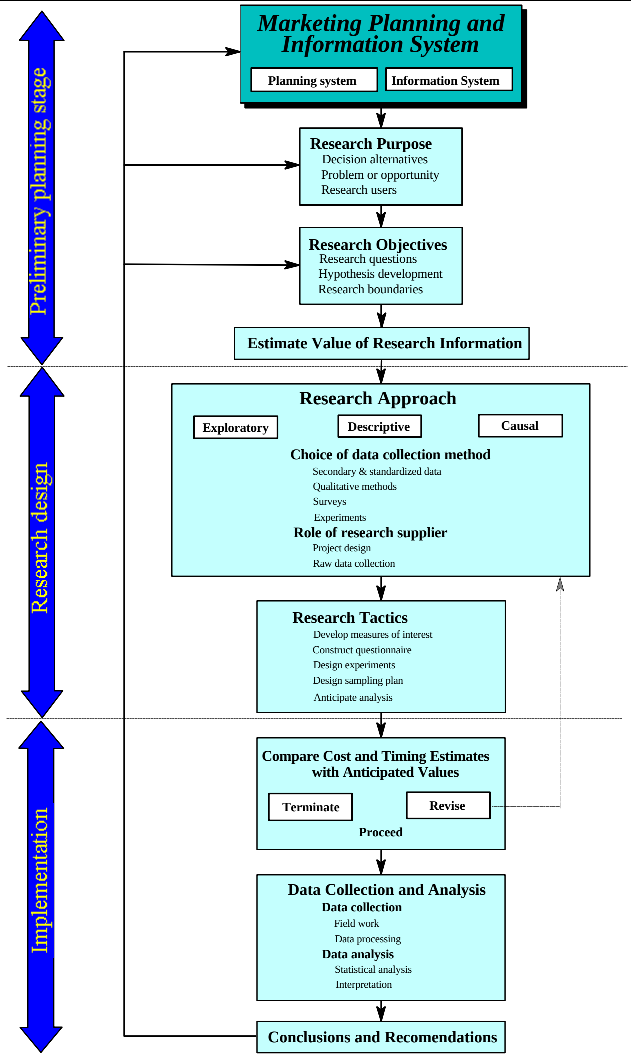


Diagram 4: *Marketing Research Process*

In this case study, the marketing and economics aspects proved the most rewarding in terms of understanding the GA industry. More importantly it was most revealing regarding the shortcomings of other viability/feasibility exercises in GA—that no in-depth work has been done on market research and financial viability of such ventures.

Aviation manufacturers are quite adept at utilising SE through their design, manufacture, and implementation of the physical product. However this case study highlights a sadly absent holistic approach that would otherwise incorporate the 'needs definition' prior to all the expense of time, resources etc. Adopting the practices of EIA632 'Processes for Engineering a System' will enhance manufacturing outcomes provided the system considers all stakeholders and their respective needs.

7 Conclusion

A systematic approach such as the procedure discussed herein to define needs greatly improves the likelihood that a proposed aeronautical product meets the market and is therefore profitable.

Aviation designer need to analyse and evaluate rather than continue with the 'wouldn't it be great if' approach. Having the best widget may achieve a 'warm fuzzy' but if nobody wants your widget, then it won't get off the ground. This limited approach will more likely achieve a liquidity problem. The way to profitably manufacture specialised/niche products is to adopt SE methodology that will accurately formulate the 'needs definition' and predict demand, rather than a pursuit of esoteric technological products that nobody wants.

Through the case study discussed in this paper the SE methodology revealed that the requirements of future GA engines can be summarised

1. ***Power***: Commercial viability of future GA aero engines production will likely require that the engine design will be adaptable to a variety of rated power/aspiration methods configurations, with appropriate weight and size.
2. ***Fuel***: Future successful aero engines will likely use unleaded mogas, 82UL or unleaded 100 avgas (if developed) or ideally avtur.
3. ***Environmental***: Aero engines of the 21st century will be adaptable to increasingly stringent noise and emission controls. This would indicate the use of modern technology for clean efficient operation. Examples include sequential direct injection, (computerised) Full Authority Digital Engine Control (FADEC) system—throttle, fuel flow, fuel & ignition timing, knock detection/control, propeller control. Future engines will likely have smaller diameter, more efficient multi-blade propeller and/or efficient reliable reduction systems to control tip vortex noise generation.
4. ***Return on Investment***: Before the engine manufacturer can expect profitability, there must be a demonstrable benefit for the aircraft owner/operator /manufacturer or there will be few sales.

In this case study, SE methodology evaluated the viability of engine manufacture, and the impact of its cost/benefit for aircraft owners/operators/manufacturers. The 'needs definition' process is useful in assessing the likely configuration of aero engines that will succeed in the GA market.

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Appendix A. ENGINE MANUFACTURERS

Appendix A1. Current Manufacturers

❈ **Teledyne Continental Motors** (TCM) (Mobile, USA) produce <50% of its full model range—no geared-engines. Recent developments include IO-550 (enlarged-bore IO-520)—the Tiara series (no longer produced). With only limited work on liquid cooling (eg Voyager engines & liquid-cooled cylinders) TCM seems to be reducing R&D and thus unlikely to meet imminent challenges—fuel efficiency, noise and emission controls, and alternate (unleaded) fuels indicated for future aircraft.

❈ **Textron Lycoming** (Lycoming) (Williamsport, USA) produce ≈40% of its full range of engines. Like TCM, Lycoming seems uncommitted to R&D, and their range of engines also continues to diminish. Geared-engine production is discontinued. Their recently introduced IO-560 series (enlarged-bore IO-540) continues to have nagging reliability problems. Apart from some experiments with unleaded fuels in existing (perhaps modified/de-rated) engines, Lycoming appears not to be meeting the challenges for future aero engines.

❈ **PZL** (Poland) & **National Aircraft Engine** (China) produce a range of Soviet designed radial engines. PZL also make aero engines (60-235HP) based on old Franklin (USA) designs—R&D effort is unknown—engines rarely used in western aircraft.

❈ **Rotax** & **Norton** each produce engines for ultralite, minimum & light aircraft types (<<200HP).

Appendix A2. Engine Developers

Of the several engine developers identified, only Orenda has type certification (TC) or supplemental type certification (STC). Claimed engine performances are unverified and should be viewed cautiously.

1. Castlemaine Rod Shop (Australia) has expended ≈AU$250,000 developing a liquid-cooled naturally aspirated V8 engine (454-572.5in^3 ≥415HP 0.59-0.87lb/HPhr—needs dramatic improvement). Tests showing promising power/weight, excludes reduction belt-drive—crankshaft not propeller shaft power/torque (reduction system can significant influence power/weight).

2. Orenda Recip Inc (Canada) purchased (late 1994) Thunder Engines' (USA) US$12M abandoned V8 (430-700HP turbocharged & normally aspirated). The development engines have good power-weight ratio and fuel efficiency (as low as 0.42lb/HPhr). Originating in 1978, it took unknown additional funds and 4 years to TC a turbocharged 600HP engine—only 1 STC for retrofitting DHC-3 Single Otter January 2000. Orenda's active STC programs include King Air C90B, & Twin Commander. These aircraft are in flight-testing for STC issuance. Orenda claims flight data on C90, Twin Commander and DHC-3 confirm improved performance in takeoff, ROC, speed & fuel consumption. Other programs include pressurised Navajo, Cessna 421, BritNorm BN-2, Air Tractor[8], DHC-2 Beaver, and AviaBellanca Skyrocket 3.

3. Canadian Airmotive (Canada)—modified Honda Civic engine (≈100HP) with belt-reduction. Claim low cost, fuel efficiency engine with equivalent power/weight to air-cooled engines—likely suitable for light singles and smaller aircraft.

4. In-Tech International (USA) dynamometer-tested an avtur-fuelled turbocharged engine (liquid-cooled in-line 3 cylinder 2-stroke diesel, 650HP). Available parameters include exceptional power-weight ratio, although rated-power claims lack authentication. Fuel consumption is not published. Seemingly, development ceased 1991.

5. Zoche Engines (Germany) have published limited data on their avtur-fuelled air-cooled 2-stroke radial diesel. They propose two models—a single bank 4-cylinder (150HP), and dual bank 8 cylinder (300HP). Claimed power-weight ratios are good, while fuel consumption is excellent, although the relationship between the two engines' power and fuel consumption raises authenticity concerns.

6. Light Power Engine Company (USA) claims to be developing a range of engine from 200-1200HP. The company claims to have direct drive engines to 600HP. Their aviation effort is direct towards non-FAR33 use (racing/experimental aircraft).

7. Eagle Engine Manufacturing (USA) has designed/modified liquid-cooled V8 engines (400-739 in3) primarily for experimental/ag-aircraft.

8. Geschwender Aeromotive (USA) have liquid-cooled turbocharged & naturally aspirated V8 engines (330-600HP, 351-460in3 belt-reduction) that have been fitted to ag-aircraft9.

9. Toyota (Japan) are understood to have done some development work on modifying their V8 Lexus engine—no details are currently available.

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8 PA-31P Navajo, Cessna 421, BritNorm BN-2 and Air Tractor are amongst 64 (18 for V8 variants) candidate retrofit aircraft first identified in masters thesis DIXON R p62

9 Piper Pawnee Brave, Cessna Ag-Truck, Funk 23B, and Schweizer AgCat

Appendix B. MOGAS/82UL APPROVALS

AIRFRAME MODELS APPROVED Revised 20/5/96	
Aero Commander, Inc SL Industries	100
Aeronca, Inc. Bellanca, Champion, Trytek, Wagner, B & B Aviation, Citabria	Most models, 7 series and 11 series. *7KCAB
Arctic Aircraft Co, Inc., Interstate	S-1A, *S-1B1, S-1B2
Beechcraft Inc. Bonanza	35, A-35, B-35, C-35, D-35, E-35, F-35, G-35, 35R
Cessna	120, 140, 140A, 150, 150A-H, 150J-M, A-150K-M, 152**, A152**, 170, 170A, 170B, 72, 172A-E, 172F (T-41A), 172G, H, P172, 172I, K, L, M, 175, 175A, B, C, 177,180, 180A-H, 180J 182, 182A-P, 305A (O-1A), 305B, 305E (TO-1D, O-1D, O-1F), CP-55, CP-65, CS-65
Commonwealth, Inc. Skyranger and Rearwin	175, 180, 185
Ercoupe, Inc. Airco, Skyranger and Rearwin	415C, D, E, G, 415-CD, F-1, F-1A, A-2, A-2A, M10
Funk	B-85C
Grumman, Inc. Gulfstream American	AA-1, -1A, -1B, -1C, AA-5, -5A
Luscombe, Inc. Temco	8 Series, 11A
Maule	M-4, Most models
Mooney	M-18C, -18C55, -18L, -18LA
Piper	E-2, J-2, J-3 (Most models), J-4 (Most models), J-5 (Most models), PA-11 (Most models), PA-12 (Most models), PA-14, PA-15*, PA-16, PA-17, PA-18 (All models), PA-19 (All models), PA-20 (All models), PA-22(Most models), PA-28-140, -150, -151
Porterfield, Inc. Rankin & Northwest	305C (O-1E), 305D (O-1G), 305F
Stinson	108 Series*, HW-75, 10
Superior Aircraft Co, Inc.	LCA, LFA* Culver, Cadet
Taylorcraft	A, BC (Most models)
Varga	2000C, 2150, 2150A, 2180
NOTE: *Airframe approvals only. **Requires engine modification	

Table 1: Airframe *Models Approved for mogas*

TCM ENGINES	
A-40, -2, -3, -4, -5 A-50-1, -2, -3, -4, -5, -6, -7 A-50-8, -9 A-65-1, -3, -6, -7, -8, -9, A-65-12, -14 A-75-3, -6, -8, -9 C-75-8, -12, -15 C-85-8, -12, -14, -15 C-90-8, -12, -14, -16 C-125-1, -2 E-165-2, -3, -4 E-185-2, -5	E-185-1, -3, -8, -9, -10, -11 C-145-2, -2H, -2HP O-170-3, -5, -7 O-200-A, -B, -C O-300-A, -B, -C, -D, -E GO-300-A, -B, -C, -D, -E, -F E-225-2, -4, -8, -9 O-470-A, -E, -J O-470-K, -L, -R, -S O-470-11, -11B, -15 O-470-4, -13, -13B
LYCOMING ENGINES	
O-235-C O-235-C1B O-235-C1, -C2, -E1, -E2 O-235-H2 O-235-L2C, K2C (modified for 80 octane)*	O-290, 0-290-A, AP, -B, -C, -CP,-D O-290-D2, -D2A, -D2B, -D2C O-320-A, -C, -E O-540-B1A5, -B1B5, -B1D5, -B2A5, -B2B5, -B2C5, -B4A5, -B4B5
NOTE: *Requires engine modification	

Table 2: Engine *Models Approved for mogas*[10]

10 http://www.eaa.org/education/fuel/approved.html Experimental Aircraft Association, Oshkosh, USA 1999