Australian Government
Australian Renewable Energy Agency

Optimization of Central Receivers for Advanced Power Cycles

Project results and lessons learnt

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Executive Summary

The project aimed to develop an “Integrated Central Receiver System Model” capable of optimising the design of both the heliostat field and solar receiver for high-temperature CSP systems. The project also investigated the quality and durability of heliostat components and established a life cycle cost model for heliostats. The outcomes of the activities were used to demonstrate the optimised design of a high-temperature CSP system, to create a public version of the optimisation software with a graphical user interface, and for sensitivity studies on the impact of the heliostat to the performance and economics of the system. An outline of the project achievements is provided below.

Various heliostat component testings (accelerated linear actuator test, accelerated mirror reflectivity degradation test, wind effect test for heliostat tracking error, mirror shape degradation analysis), have been designed, performed, and are also under continuous data collection. The investigated or estimated heliostat quality were used for simulating its impact on the system performance. A heliostat cost model has been developed and life cycle heliostat costs of different designs have been estimated.

Heliosim-ICRSM is a plugin for CSIRO’s Workspace software that that provides the full capability of the “Integrated Central Receiver System Model” developed in this project. By combining a GPU accelerated ray tracing engine that allows surface meshes description of complex receiver geometries, with a detailed heat transfer model including surface-to-source radiation exchange and CFD simulation of convective cooling, Heliosim-ICRSM provides a unique capability for optimising and simulating the heliostat field and receiver components of a CSP facility. As a case study, the optimised design for a 10 MW_t sodium receiver system has been demonstrated. Heliosim-PI, a standalone software package with a graphical interface, has been also developed as a version of the integrated model that will be publicly disseminated. In addition, a second public standalone software package, Heliosim-NSEC, has been developed to provide a tool for quickly performing ray tracing simulations of CSIRO’s experimental facility in Newcastle. Windows, Linux and Mac installers for all three software packages have been uploaded to the CSIRO Data Access Portal. Heliosim-PI and Heliosim-NSEC will be made publicly accessible following completion of the supporting documentation and passing an internal CSIRO review for publicly available material. Heliosim-ICRSM will be retained for use within CSIRO and by authorised project partners.

Through various sensitivity studies with various tools including Heliosim-ICRSM, high-level guidelines (in terms of expected performance increase and acceptable cost increase) for heliostat development have been provided. Regarding receiver design recommendations, upper performance boundaries for two high temperature receivers (liquid Sodium and sCO_2 receivers) have been provided along with relevant sensitivity studies.

Project Overview

Project summary

This project focused on better understanding the relationship between heliostats and receivers when optimising central receiver systems for advanced power cycles, particularly for the temperature range where the most attractive CSP options lie. The key objectives were to (1) understand and quantify the full life cycle cost of heliostats, (2) develop an integrated model that uses detailed ray tracing, CFD and heliostat costing to optimise central receivers for the temperature range of interest, and (3) enable the results of this project, including a suitable version of the integrated model, to be publicly disseminated. Detailed tasks to achieve the objectives were identified in four different groups of activities.

1. **Understand and quantify the full life cycle cost of heliostat based on both existing and new concepts.**

    1.1. Undertake field trials and accelerated life testing of small heliostats at CSIRO and one other Australian site.

    1.2. Undertake comparative analysis with larger heliostats based on Sandia's long experience with large heliostat operation and costing.

    1.3. Use the methodology of Sandia's previous comprehensive heliostat cost reduction study (which was ostensibly for large heliostats) to evaluate small heliostats.

2. **Develop an integrated model that uses detailed ray tracing, CFD and heliostat costing to optimize central receivers for the temperature range 600-800°C.**

    2.1. Review ray tracing software suitable for the application and assess for preferred model.

    2.2. Undertake any ray trace model modifications needed to ensure it is computationally efficient for large fields.

    2.3. Develop the family of receiver geometry configurations in a form suitable for CFD analysis.

    2.4. The family of receivers will include direct and indirect receivers, and consider solid particle receivers as well as liquid and gaseous fluids.

    2.5. Combine the ray tracing and CFD in the preferred manner.

3. **Enable the results of this project, including a suitable version of the integrated model, to be publicly disseminated.**

    3.1. Validate the model with support of NREL

    3.2. Prepare the format of the model for public dissemination. (CSIRO ultimately responsible for public dissemination of the model)

4. **Establish boundary conditions and recommendations for future heliostat designs and receiver designs.**

4.1. Examine overall system model cost sensitivity to heliostat parameters such as errors, size, shape, component longevity.
4.2. Provide recommendations for the required boundary conditions that heliostat developers and manufacturers will need to be aware of. Consider fully installed and life cycle cost, not just manufactured cost.
4.3. Provide receiver concepts that provide optimum performance for this temperature range.

Project scope

If concentrating solar power (CSP) technology is to be widely adopted for electricity production, its cost must be substantially reduced, similar to the cost reduction achieved by solar photovoltaic technology in recent years. The key solar components that will drive down cost are heliostats and receivers which together operate to provide temperatures in the 600-800^{o}C range, as this allies with high efficiency turbine technologies such as supercritical CO_2 Brayton cycles. To date the solar towers built commercially have been for considerably lower operating temperatures.

The solar field, with thousands of reflectors called heliostats, and the solar receiver, to absorb the solar energy and to transfer it into the heat transfer fluid, are major components of the CSP system. Since the high-temperature system is more prone to be impacted by heat loss and various constraints related to heat transfer and material, the optimum system design is also impacted by these factors, thus the need of a comprehensive optimisation model becomes more critical.

The project aimed for the development an integrated central receiver model capable of optimising the design of the heliostat field and solar receiver for high-temperature CSP systems. It also investigated the quality and durability of heliostat components and established a life cycle cost model for heliostats. The outcomes of the activities were used to demonstrate the optimised design of a high-temperature CSP system, to create a public version of the optimisation model with a graphical user interface, and for sensitivity studies on the impact of the heliostat to the performance and economics of the system.

The targeted objectivities were achieved through various experimental and theoretical activities in collaboration with three project partners: NREL, SNL, and Vast Solar. The activities included (1) designing and building a new testing devices for heliostat component, (2) field test of heliostats (in collaboration with Vast Solar), (3) test data analysis, performance modelling and economic modelling (in collaboration with SNL), and (4) optimisation model development and accelerated mirror degradation test (in collaboration with NREL)

Outcomes

1. Life cycle cost of heliostat

AN accelerated actuator life cycle test rig has been designed, fabricated and used for investigating degradation rates of actuators. High reflectivity mirrors from 5 different manufacturers are under 5 times accelerated degradation test using a weather chamber at NREL. Field testing for heliostat structures and the effect of wind has been completed using heliostats equipped with accelerometers. The field test collected data over a 12 month period at Vast Solar's facility in Forbes, NSW. An analysis method to estimate wind-induced displace magnitude was validated using a manually exited heliostat in the solar field at CSIRO in Newcastle. Heliostat facet degradation has been tested using multiple years of data from CSIRO's Solar Field 2. No facet shape degradation was detected over the life of the field so far.

A costing method for large scale heliostats developed by SNL for the ATS 148 m^2 heliostat was referred and used in a modified form for cost estimation of small CSIRO heliostat. A new model for estimating heliostat life cycle cost has been developed in conjunction with the ARENA Low Cost Heliostat project.

Performance parameters of small heliostats have been provided for 2 structures and 2 actuators options. Life cycle costs for 3 different sized heliostats (5.06, 7.22, and 14.44 m^2) were estimated using the new costing model.

2. Integrated central receiver system model

Heliosim-ICRSM is a plugin for CSIRO's Workspace software that provides the full capability of the "Integrated Central Receiver System Model" developed in this project. By combining a GPU accelerated ray tracing engine that allows surface meshes description of complex receiver geometries, with a detailed heat transfer model including surface-to-source radiation exchange and CFD simulation of convective cooling, Heliosim-ICRSM provides a unique tool for optimising and simulating the heliostat field and receiver components of a CSP facility.

CSIRO's 'Heliosim' ray tracing software was selected for use in the integrated model. A number of candidate ray tracing software packages (namely Tonatiuh, Soltrace and Tiesol) were considered, however the benefits of using CSIRO's own ray tracing tool were numerous – access to and familiarity with the source code, ability to handle complex receiver geometries such as cavity receivers, and good computational performance.

The family of receivers able to be simulated by the Heliosim-ICRSM software encompass three variants of the tubular receiver concept:

- Open cavity receiver (i.e. similar to the PS10 receiver geometry)
- Circular aperture cavity receiver (as above but with a constrained circular aperture)
- Cylindrical external receiver (i.e. similar to the Gemasolar receiver geometry)

3D volume meshes and 2D surface meshes describing these receiver types are parametrically created at runtime using the SALOME CAD software. The 2D surface meshes are used for both the ray tracing and heat transfer calculations, whilst the 3D volume mesh enables OpenFOAM CFD simulations to be performed to obtain a more accurate estimate of the convective cooling losses due to external air flow. Externally created surface meshes describing the receiver can also be imported by the user.

The initial software release enables the user to consider tubular receivers with either nitrate salt, liquid sodium, CO_2 or air as the heat transfer fluid. The modular nature of the software, however, does not preclude the option of incorporating additional heat transfer models. As a case study, the optimised design of a 10 MW_t liquid sodium receiver system has been demonstrated.

3. Integrated CRS model for public dissemination

Three software packages have been developed: Heliosim-ICRSM, Heliosim-PI and Heliosim-NSEC. Heliosim-ICRSM is a plugin for CSIRO's Workspace software, and is the complete and unrestricted version of the “Integrated Central Receiver System Model”. Heliosim-PI is a standalone application with a graphical interface, and is the version of the integrated model that will be publicly disseminated. Heliosim-NSEC is also a standalone application with a graphical interface, and provides a ray tracing tool for CSIRO’s experimental facility in Newcastle. Windows, Linux and Mac installers for all three software packages have been uploaded to the CSIRO Data Access Portal. Currently the software is available for download by users with CSIRO authorised credentials (i.e. CSIRO staff and project partners).

4. Design boundary and recommendations

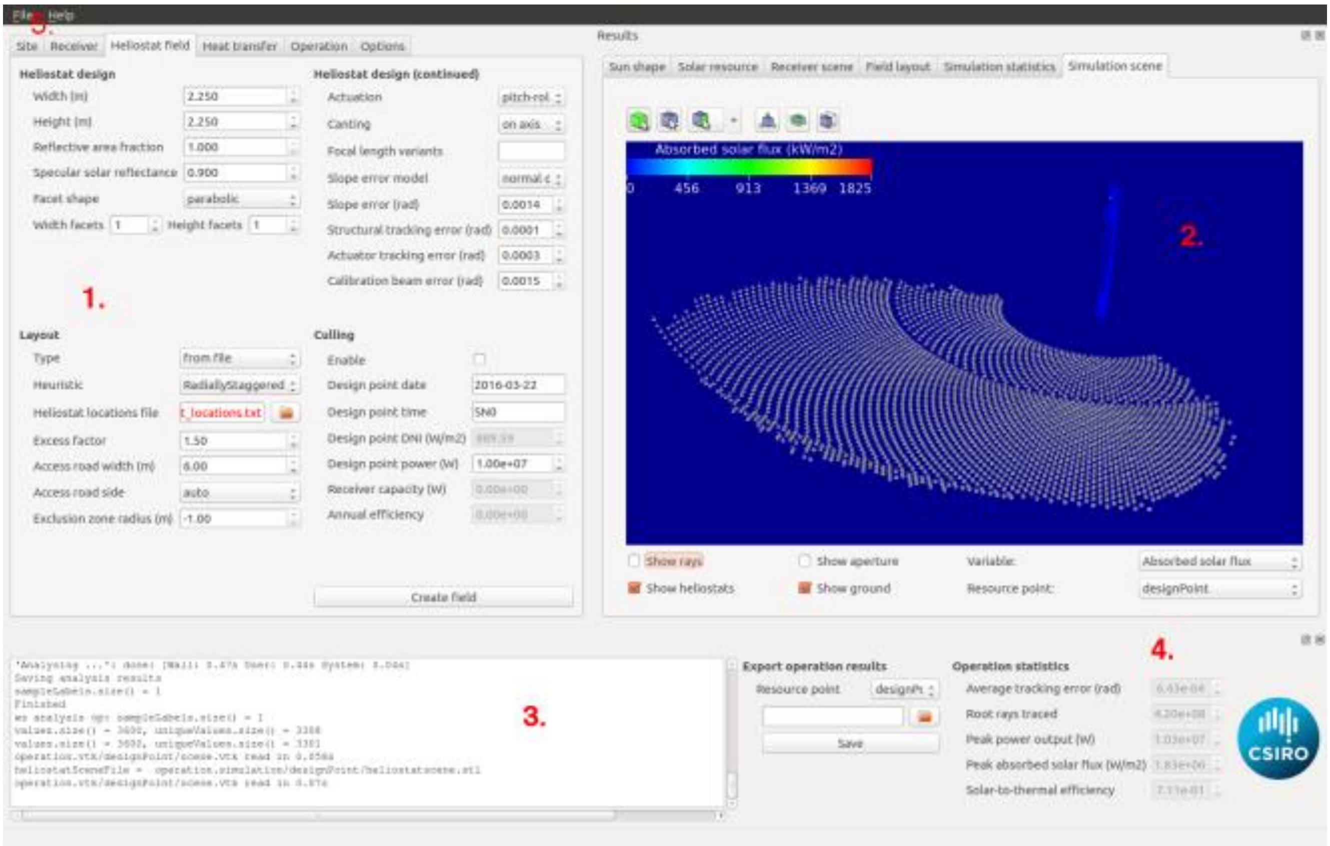
The sensitivity of optical efficiency to heliostat size (5.06 to 148.8 m^2) and slope error (1 to 2 mrad) has been investigated for a 250 MW_t central receiver system with different receiver sizes. The study revealed that optical solar field efficiency of a system with a smaller high-flux receiver is more sensitively decreases as the heliostat size and slope error increase compared to the case with a larger low-flux receiver.

The sensitivity of system performance for a 10 MW_t liquid sodium receiver to heliostat component quality (which was quantified in the model as tracking error) has also been investigated using Helisim-ICRSM. The simulation results showed that for this particular CSP system, the performance difference created by component quality-induced tracking errors is very minor.

The result of the sensitivity studies were then linked with the cost modelling to provide guide lines of future heliostat development. Component longevity analyses have not been carried out since no notable changes with mirror slope error and reflectivity (which were expected to be degraded over time) were monitored from 3 years of CSIRO solar field data and also from NREL’s experiences with longer term accelerated mirror exposure tests.

Using the LCOE cost modelling method, the impact of various heliostat design parameters on cost have been investigated: (1) the impact of heliostat size-created performance increase and O&M cost increase, (2) the impact of component quality-related performance increase and heliostat cost increase, and (3) the impact of component quality-related heliostat breakdown and heliostat cost reduction.

Ideal heat transfer conditions of high temperature tubular receivers (liquid Sodium and sCO_2 receivers) have been identified through combined heat transfer and material stress analyses. The obtained ideal heat transfer conditions and corresponding performance and design parameters for the receiver provide design boundaries for the best performing receivers. Additionally, sensitivity studies on off-ideal design and off-design operation has also been carried out. The necessity of an accurate flux distribution control along the flow path (to meet the more constrained allowable material stress limit in the high temperature zone) is one of the key findings to be noted for the design and operation of receivers.



Heliostat design

Width (m): 2.250
Height (m): 2.250
Reflective area fraction: 1.000
Specular solar reflectance: 0.900
Facet shape: parabolic
Width facets: 1
Height facets: 1

Heliostat design (continued)

Actuation: pitch-rol
Canting: on axis
Focal length variants:
Slope error model: normal c
Slope error (rad): 0.0014
Structural tracking error (rad): 0.0001
Actuator tracking error (rad): 0.0003
Calibration beam error (rad): 0.0015

Layout

Type: from file
Heuristic: RadiallyStaggered
Heliostat locations file: t_locations.txt
Excess factor: 1.50
Access road width (m): 6.00
Access road side: auto
Exclusion zone radius (m): -1.00

Culling

Enable ☐
Design point date: 2016-03-22
Design point time: SN0
Design point DNI (W/m2):
Design point power (W): 1.00e+07
Receiver capacity (W): 0.00e+00
Annual efficiency: 0.00e+00

☐ Show rays
☑ Show heliostats
☐ Show aperture
☑ Show ground
Variable: Absorbed solar flux
Resource point: designPoint

Export operation results

Resource point: designPt

Operation statistics

Average tracking error (rad): 6.43e-04
Root rays traced: 4.20e+08
Peak power output (W): 1.03e+07
Peak absorbed solar flux (W/m2): 1.83e+06
Solar-to-thermal efficiency: 7.11e-01

Figure: The Heliosim-PI graphical user interface (1: main control panel, 2: results dock, 3: log dock, 4: statistics and export dock, and 5: drop down menus).

Transferability

1. Equipment, “know-how” and results of heliostat test and heliostat component test:
   - Linear actuator accelerated test device is available to be used by external clients or collaborators.
   - Heliostat wind effect test setup, (installed at both CSIRO Newcastle and Vast Forbes), instruments and analysis know-how are available for further scientific investigation and testing new heliostats by external clients or collaborators.
   - Test results of accelerated mirror reflectivity degradation (currently under continuous test at NREL) can be shared on request if mirror manufacturers agree.
2. Integrated central receiver system modelling software (after internal reviews for public release by CSIRO):
   - Heliosim-NSEC will be downloadable from the CSIRO Data Access Portal (https://data.csiro.au) to assist in the optical design of future test devices for CSIRO’s Solar Field 2 in Newcastle.
   - Heliosim-PI will be downloadable from the CSIRO Data Access Portal (https://data.csiro.au) as a powerful and unique tool for designing and optimising the heliostat field and receiver in a combined way.
   - Heliosim-ICRSM will be retained for use within CSIRO or by external clients and collaborators for the detailed optimisation and design of central receiver systems.

Publications

Conference presentations with a full paper

1. Potter et al., Optimized design of a 1 MW_t liquid sodium central receiver system, 2015 Asia-Pacific Solar Research Conferenced, 8~9 Dec, 2015, Brisbane, Australia.
2. Kim et al., Ideal heat transfer conditions for tubular solar receivers with different design constraints, SolarPACES 2016, 11~14 Oct., Abu Dhabi, UAE.
3. Anderson et al., Corrosion of second surface heliostats in costal environment, 2015 Asia-Pacific Solar Research Conferenced, 8~9 Dec, 2015, Brisbane, Australia.
4. Dunbar et al., Heliostat motion under real wind loads in central receiver solar thermal plants, 2015 Asia-Pacific Solar Research Conferenced, 8~9 Dec, 2015, Brisbane, Australia.

Conference presentations with an abstract

5. Potter et al., An integrated model for optical and thermal analysis of central receiver systems, SolarPACES 2015, 13-16 Oct, 2015, Cape Town, South Africa.
6. Kim et al., Optimum design of tubular central receivers for concentrated solar power systems, 5th Asia-Pacific Forum on Renewable Energy, 04~07 Nov, 2015, Jeju, Korea.
7. Potter et al., An integrated computational model for the optimization of central receiver systems, An integrated model for optical and thermal analysis of central receiver systems, 10th ASME Int. Conf. on Energy Sustainability, Charlotte, USA, 2016.
8. Kim et al., Analytical stress calculation for non-axisymmetrically heated solar receiver and comparison with FEA result, 10th ASME Int. Conf. on Energy Sustainability Charlotte, USA, 2016.
9. Potter et al., Coupled heliostat field and receiver optimization for central tower CSP facilities, 2016 ASIA-pacific Solar Research Conference, Canberra, Australia, 2016.

Submitted for upcoming conferences

10. Potter and Kim, Hliosim-ICRSM: An integrated model for the optimisation of central receiver CSP facilities. submitted to SolarPACES2017 (to be held in Santiago, Chile, in September, 2017)
11. Kim et al., Measurement and modelling of wind effect on the tracking error of CSIRO heliostat. (to be held in Santiago, Chile, in September, 2017)
12. Kim et al., Sensitivity study on the off-ideal design and off-design operation of tubular solar receivers. (to be held in Santiago, Chile, in September, 2017)
13. Xu et al., A study on calculating the view factor in cavity solar receivers with a multiple-surface cover. (to be held in Santiago, Chile, in September, 2017)
14. Ye et al., Comparison of optical modelling tools on sun shapes and surface slope errors. (to be held in Santiago, Chile, in September, 2017)

Other presentations and communications

1. Potter, An integrated model for optic and thermal analysis of central receivers, presented to Engie, 2 December, 2015.
2. Kim, Solar receiver design for CSP, presented to Beihang Univ. (China), 26 August, 2015.
3. Potter, Heliosim-NSEC: a ray tracing tool for solar field 2, Presented to ANU, August, 2016 / Presented in Science Swam, CSIRO Solar Group, October, 2016.

4. Potter, Optimisation of central receiver CSP facilities, presented to Thermal Focus, Jun., 2016 / presented to NREL, June, 2016.
5. Potter, Optimization of central receive CSP facilities, presented to Engie, July, 2016.
6. Kim, Solar receiver development and design in CSIRO, presented to NREL, June, 2016 / presented to Engie, July, 2016.
7. Potter et al., Heliosim-ICRSM: An integrated central receiver system model, presented to NREL, Jan., 2017.
8. Heliosim-NSEC posted in CSIRO Access Portal, January, 2017.
9. Internal communication with CSIRO IM&T on the development of Heliosim-NSEC and the collaboration with IM&T., July, 2016.
10. Heliosim-NSEC provided to a visiting scientist from CAS (Chinese Academy of Science) for transient modelling of a cavity receiver, October, 2016.
11. Updated Heliosim-NSEC package provided to ANU to assist bladed receiver design, March, 2017.
12. Heliosim-PI provided to Thermal Focus (a Chinese CSP company) as a part of heliostat technology licencing, March, 2017.
13. Heliosim-PI has been uploaded to the CSIRO Data Access Portal, March, 2017.

Intellectual Property: Patents / Licences

Heliosim-ICRSM is one of core parts of licencing CSIRO’s heliostat technology.

Awards

1. Potter et al., Award for best poster in the renewable energy stream “An Integrated computational model for the optimization of central receiver CSP facilities” 2016 ASME Power and Energy Conference, Charlotte, NC, USA.
2. Mike Collins: The John Philip Award, 2016 in recognition of heliostat technology development.

Conclusion and next steps

Testing equipment, and the associated know-how, for investigating quality and durability of heliostat component has been successfully developed. Along with the model to estimate life cycle cost of heliostats, the outcomes of the project will provide key capabilities to qualify and quantify the performance and cost of heliostats, especially small heliostats using linear actuators.

The integrated central receiver system model, Heliosim-ICRSM, provides a unique and comprehensive modelling capability not available in other existing CSP modelling packages. Models for the generation of 3D meshes describing both external and cavity receiver concepts, ray tracing of heliostat field optics, heliostat field layout optimisation, receiver heat transfer analysis including CFD simulation of convective cooling losses, material stress estimation and annual system simulation analysis are all available and can be utilised in an integrated way.

The outcomes of the project can be directly used for the detailed design and optimisation of CSP systems, and also for simulation of system operation under different constraints and strategies.

During the project period, interim and final outcomes and know-how were used for designing multiple experimental receivers and for demonstrating the solar field and receiver design capability for a commercial purpose. As such, Heliosim-ICRSM is now one of the core components of CSIRO's heliostat technology licencing.

In order to maintain and maximise the benefit of the project outcomes, some additional and continuous activities need to follow beyond the project:

- Additional and in-depth study on the wind effect to the heliostat tracking error will be interesting. Currently, a high-level estimation has been made according to the wind speed only. The analysis needs to be expanded to identify the effects of wind direction, heliostat orientation and heliostat location.
- Minimum maintenance needs to be taken for the heliostat testing device at Forbes.
- Data collection from the accelerated mirror reflectivity test at NREL will continue for a number of years, which will incur costs for consumables and labour.
- Periodic updates of the modelling software and technical supports to users are essential to maintain the publically released software. This will require time and effort from software development team.

Lessons Learnt Report: Scientific software development

Project Name: *Optimisation of Central Receivers for Advanced Power Cycles*

Knowledge Category:	Technical
Knowledge Type:	Technology
Technology Type:	Solar Thermal
State/Territory:	NSW

Key learning

The development of scientific software for public dissemination formed a key component of this project. This involved the implementation of the underlying mathematical models describing various optics, heat transfer and stress phenomena, development of supporting software libraries to provide functionalities such solvers for systems of non-linear equations, workflow management and distributed CPU execution, and the nuances of creating the graphical user interface for the public release version. Two software specialists from CSIRO's IM&T department were brought into the project to assist specifically with the development of supporting libraries and graphical user interfaces. This proved to be instrumental in delivering the public software release, as did the adoption of the Workspace software. Workspace[1] is a powerful cross-platform workflow framework that enables collaboration and software reuse that is developed by Data61, a relatively new CSIRO research unit of CSIRO. The use of Workspace allowed the transition from a text-based research code to GUI-based public software to package to occur in the relatively short period of approximately 2 years. Invaluable technical support was provided by Data61 throughout the project, allowing impressive features such as 3D visualisation and multiplatform support to be incorporated. Without Workspace and support provided by Data61 the software outputs from the project be considerably less professional in both function and appearance.

Implications for future projects

The hiring of software specialists and adoption of the Workspace software occurred in the last 2 years of the project. If software specialists and the Workspace software had been available at the beginning of the project, the path to the development of publicly releasable software package could have been streamlined (e.g. making better use of the powerful built-in Workspace plugins, and adopting a clear code style guideline to allow easier code reuse). Instead, the software was developed initially as a text-based research code, then 'ported' to become a Workspace plugin via a crude interface with the existing code base. This would have allowed more time to be spent perfecting the user interface, with is a critical feature of software that allows the results of a research project such as this to be communicated effectively to a non-specialist audience. Future projects with similar software outputs should ensure that IT personnel with experience in workflow management systems such as Workspace are available.

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[1] https://research.csiro.au/workspace/

Knowledge gap

This aspect of the project highlighted the importance of having access to IT personnel with expertise in workflow management software such as Workspace, and producing software intended for public release (i.e. cross platform with graphical user interface).

Background

Objectives or project requirements

The project aimed to develop an "Integrated Central Receiver System Model" capable of optimising the design of both the heliostat field and solar receiver for high-temperature CSP systems. A suitable version of this model was then made available for public dissemination.

Process undertaken

An existing code collection developed by the CSIRO for the ray tracing of heliostat optics for CSP applications formed the basis for the development of the "Integrated Central Receiver System Model". Additional modelling capabilities such as receiver heat transfer modelling and heliostat field layout optimisation were added to the code collection, and the ray tracing model was modified to allow for efficient simulation of facilities with large numbers of heliostats. A crude interface was then written to expose the functionality of the code collection as a plugin in the Workspace workflow management software. A workflow defining the functionality of the "Integrated Central Receiver System Model" was then developed, which was then compiled into a standalone, cross-platform executable complete with graphical user interface and supporting documentation etc.

Supporting information (optional)

Some figures illustrating the various steps in the software development process are included below. First the workflow defining the integrated model functionality was conceived in theoretical terms, Figure 1. *A plugin providing the required modelling capabilities was then written for the Workspace software, which was then used to create the Workspace workflow,* Figure 2. *Finally, the workflow is integrated into a standalone application with a graphical user interface for public release,* Figure 3.

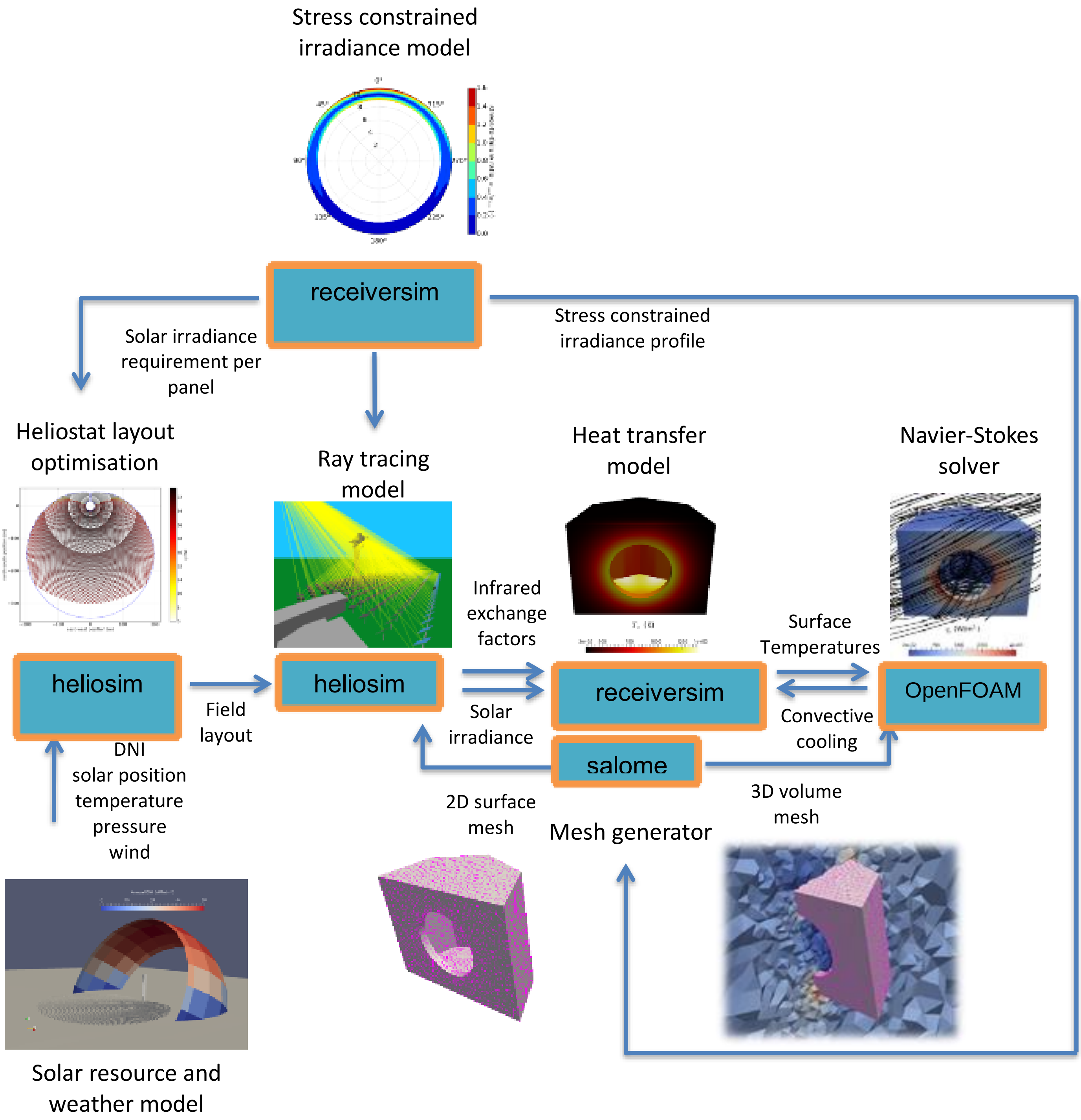
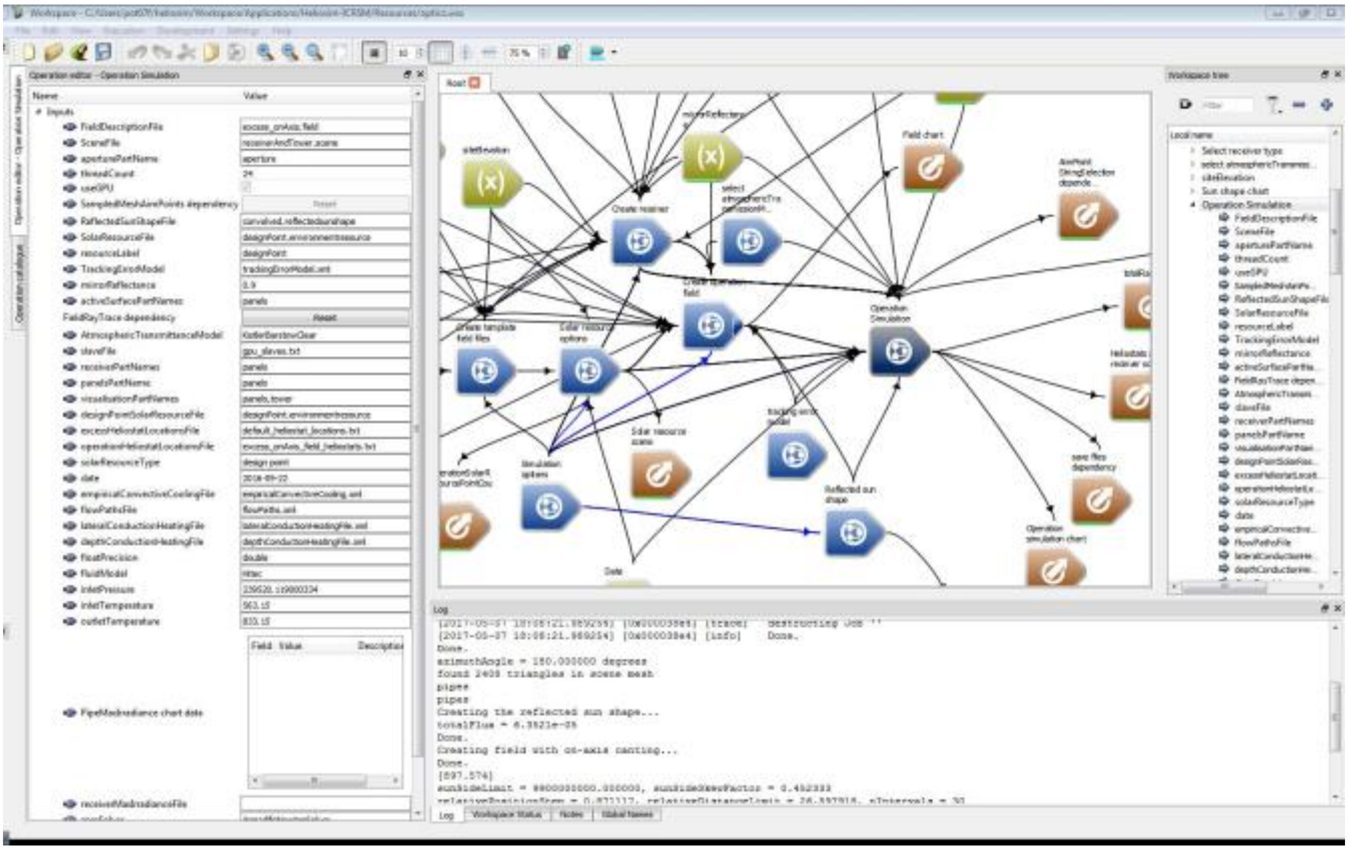
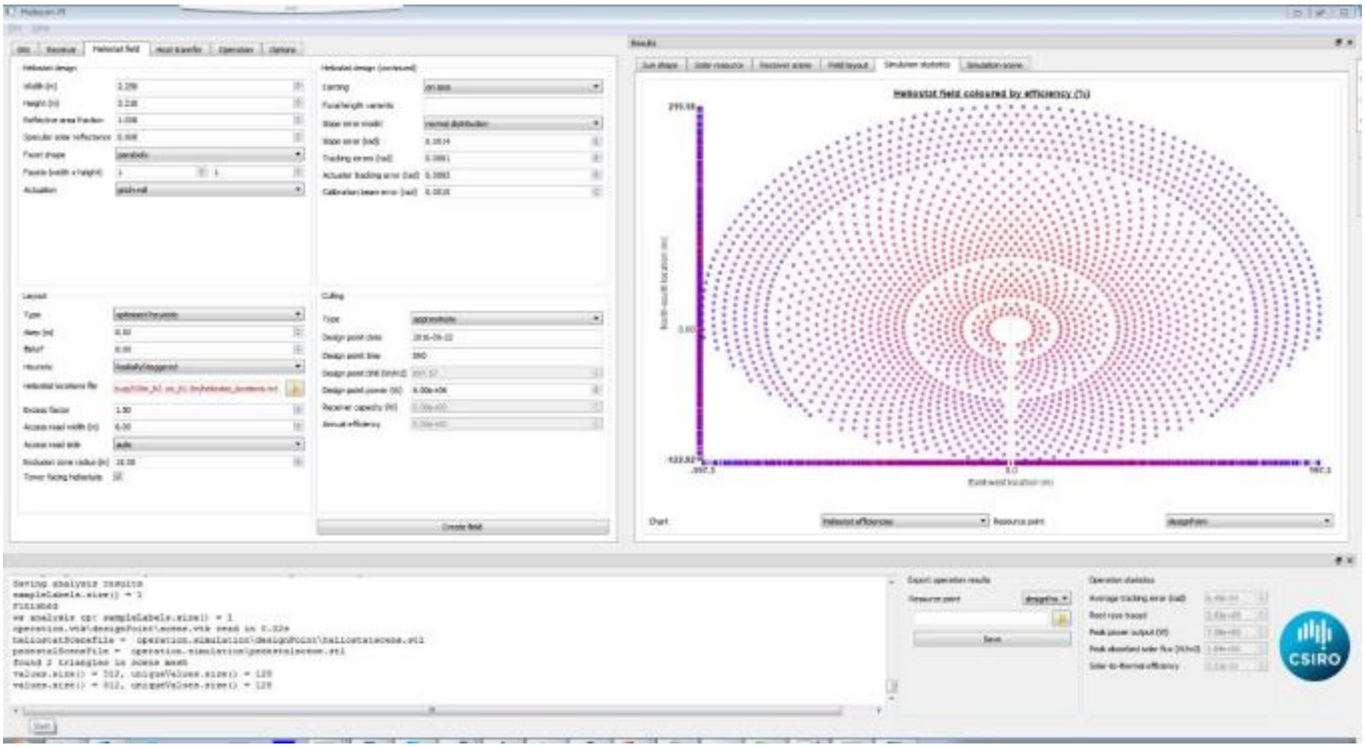


Figure 1: Flow diagram describing the functionality of the integrated central receiver system model.



```
[2017-05-07 10:06:21.969254] [0x000038e4] [info]    Done.
Done.
azimuthAngle = 180.000000 degrees
found 2408 triangles in scene mesh
pipes
pipes
Creating the reflected sun shape...
totalFlux = 6.3521e-05
Done.
Creating field with on-axis canting...
Done.
[897.574]
sunSideLimit = 9800000000.000000, sunSideSkewFactor = 0.452333
```

Figure 2: Using the Heliosim-ICRSM as a plugin in Workspace to create the workflow defining the functionality of the public release software.



```
Saving analysis results
sampleLabels.size() = 1
Finished
ws analysis cp: sampleLabels.size() = 1
operation.vtk\designPoint\scene.vtk read in 0.02s
heliostatSceneFile =  operation.simulation\designPoint\heliostatscene.stl
pedestalSceneFile =  operation.simulation\pedestalscene.stl
found 2 triangles in scene mesh
values.size() = 512, uniqueValues.size() = 128
values.size() = 512, uniqueValues.size() = 128
```

Figure 3: The graphical user interface for the version of the software for public release, Heliosim-PI.

Appendix

Keywords

Concentrated Solar, CSP, Heliostat, Central Receiver, Optimization, Workspace

Glossary of terms and acronyms

CFD: Computational Fluid Dynamics

CSIRO: Commonwealth Scientific and Industrial Research Organization

CSP: Concentrated Solar Power

Heliosim-ICRSM: Integrated Central Receiver Systems Model

Heliosim-PI: Public version of Integrated central receiver system model

NREL: National Renewable Energy Laboratory, USA

sCO_2: supercritical Carbon Dioxide

SNL: Sanial National Laboratory. USA

SolarPACES; Solar Power And Chemical Energy Systems